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Research Article

Life Cycle Ecological Footprint Reduction for a Tropical Building

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Rapid urbanization significantly impacts natural resource demands and waste management in the construction sector. In this study, a novel methodology has been developed that could assess the overall environmental impact of a building during its lifespan by considering resources such as building materials, energy use, emissions, water, manpower, and wastes. The proposed method can estimate the life cycle ecological footprint (EF_T) of a building. The result indicates that 957.07 global hectares (gha) of bioproductive land are required during the lifespan of the case building. The CO_2 absorption land is the most significant bioproductive land in the EF_T of the building. The low environmental impact of building materials may reduce the ecological footprint (EF) of buildings, and using renewable energy can also reduce the operational EF of a building. The proposed building materials and solar PV systems have the potential to reduce the building's life cycle environmental impact by up to two-thirds. The EF assessment of all existing and proposed buildings may be examined in order to execute strategies for a sustainable construction sector.

1. Introduction

Rapid urbanization influences natural resource demand and energy use as well as greenhouse gas (GHG) emissions [1, 2]. The construction industry is accountable for 40% of the global materials demand [3], 32% of the global energy consumption, and 19% of the global energy-related GHG emissions [4]. The Indian construction industry is expected to grow annually at 5.6% during 2016–20, and it may grow annually up to 7.1% by 2025 [5]. However, one-quarter of the total consumed primary energy and one-third of the total generated electricity are consumed in Indian buildings [6, 7].

In the entire lifespan of a building, energy, construction materials, manpower, construction and demolition (C&D) waste, water, transportation, and GHG emission are considered to be the major factors that have an ecological impact [8–11]. Many studies on life cycle energy [12, 13], emissions [14], C&D waste [15], transportation [16], and water consumption [17] in buildings have been reported. The estimated material use in India is projected to be nearly 15 billion tonnes by 2030, and it will further increase up to 25 billion tonnes by 2050 [18], while total C&D waste generated in the country in 2015 was about 716 million tonnes [19]. Bardhan analyzed that the building material production and building construction phase required water up to 27 kilolitres/m^2 of the floor area [17]. Waste is generated in every phase of the building, while the maximum C&D waste is generated when the building is demolished [15]. The energy consumption and CO_2 emissions by the transportation of building materials and C&D waste are significantly low as compared to the total life cycle energy consumption and emissions of the building [16]. Ding examined the energy consumption pattern during the different life stages of case study buildings; the study suggested that the operational phase and the construction phase of the building are responsible for 62% and 38% of the total life cycle energy

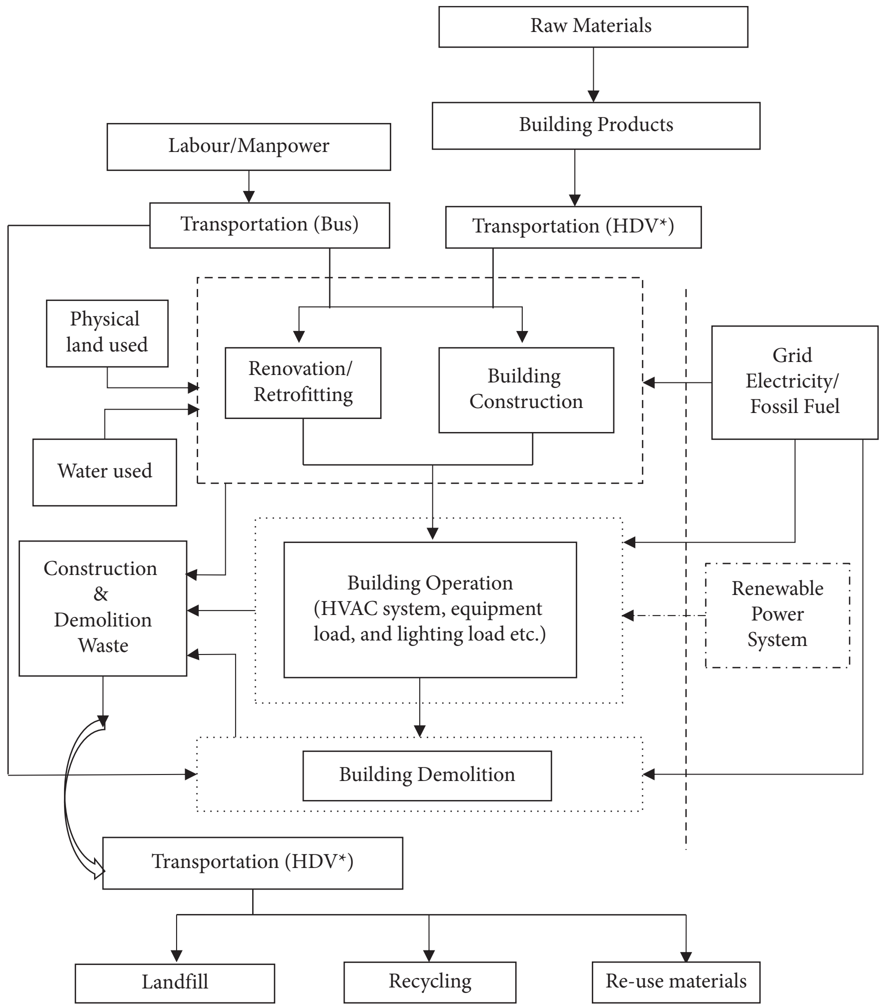

Figure 1: System boundary for the analysis of a building (self-made). ∗Heavy-duty vehicle (HDV).

consumption, respectively [20]. Suresh et al. assessed that the total annual GHG emissions of TERI University, Delhi, is approximately 0.72 tCO_{2e} per capita of the campus [21]. Thus, the building sector has the potential to achieve local and global environmental objectives (i.e., United Nations, Sustainable Development Goals) [22].

1.1. Ecological Footprint (EF). The EF indicator can measure the rate of resource consumption and waste generation, and it compares with the resource production and waste assimilation rate of the planet [23]. The indicator comprises all resources/activities as input and converts them into a single output (i.e., global hectare) unit. The unit of EF is defined as "One global hectare (gha) is equivalent to one hectare of bioproductive land with world average productivity" [24].

Only a few studies have been reported for the EF assessment of buildings [25–30]. Kumar et al. reported that the life cycle ecological footprint of the Indian houses is in the range of 242–401 gha [25]. Jiaying and Xianguo examined the eco-efficiency and eco-footprint of a building; however, various assumptions such as demolition energy factors and construction, and destruction time of building are considered to estimate the environmental impact of each phase of the building [26]. Lui et al. reported that the life cycle ecological footprint of the multi-layer residential building is 0.859 ghm^2 [27]. Martínez-Rocamora et al. examined the annual EF of the Hernando Colón Hall of Residence is about 79.4 gha, while the maximum contributor was carbon absorption land (96.6% of the total bioproductive land) [28]. Gottlieb et al. had estimated that the EF of a selected school building is about 314 gha per year; the school building annually consumed bioproductive land of 160 folds of the total constructed area of the building [29]. Husain and Prakash reported the annual ecological footprint of a tropical building as 73.8 gha (i.e., the consumed bioproductive land was nearly 101 folds of the total constructed area of the case building [30].

1.2. Research Gap. Various studies attempt to evaluate the environmental impact of buildings, considering energy [7], emissions [21], or a combination of such factors [31]. Some studies also used the ecological footprint indicator to estimate the environmental impact of the entire building's lifespan [26, 30]. However, all the input resources (see Figure 1) have not been measured simultaneously to evaluate the life cycle ecological footprint of a building.

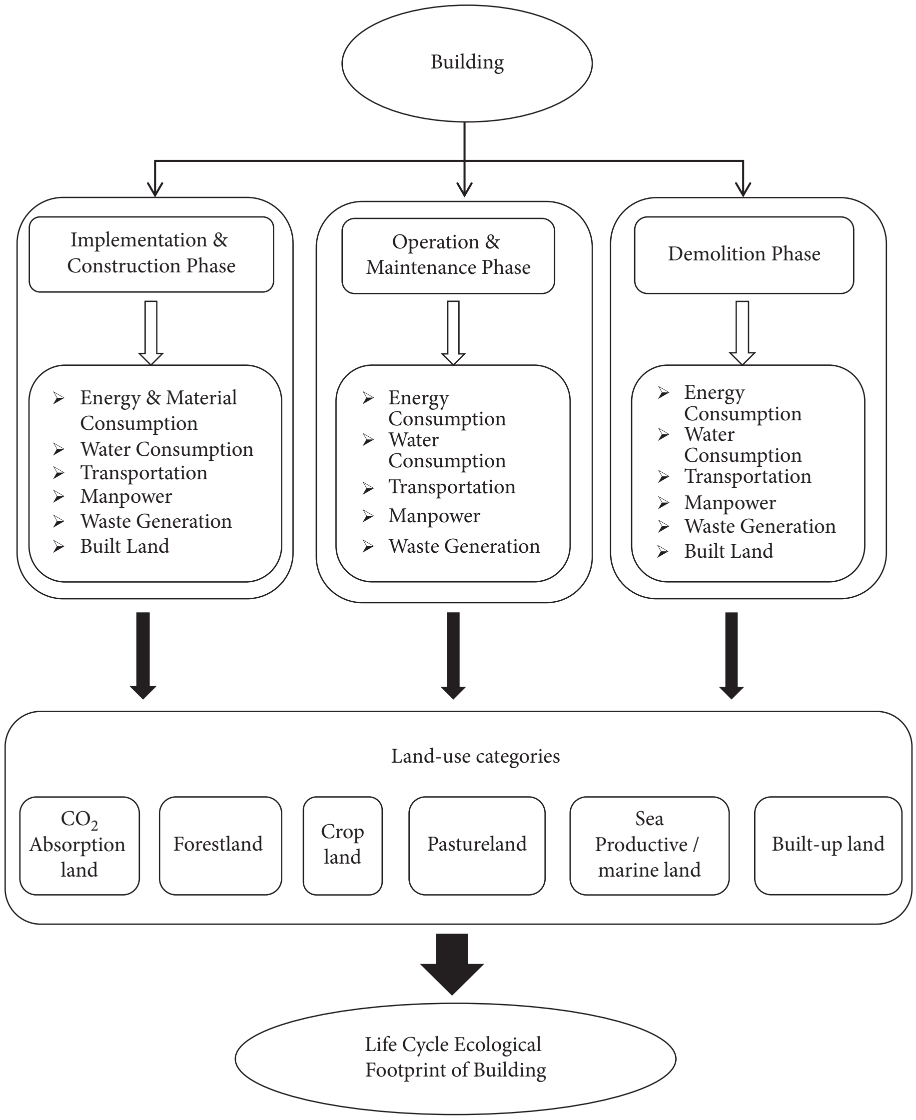

Figure 2: Flow diagram of the EF_T of a building (self-made).

1.3. Research Goal. The objective of the research work is to develop a method that can estimate the environmental impact of a building during its whole lifespan. The proposed method evaluates the building's eco-imprint on the Earth through the ecological footprint indicator. The research goal has been carried out according to the methodological flow diagram shown in Figure 2.

1.4. Advantages and Disadvantages. The research study presents a novel method for the life cycle ecological footprint assessment of a building. It integrates resource limitations (i.e., available biocapacity of the planet) and sustainability aspects over the entire lifespan of a building. The life cycle ecological footprint provides a more comprehensive assessment than the energy analysis and emission analysis [32, 33]. The study does not consider the future degradation of bioproductive land during the calculations [24]. The assumption in calculating the life cycle ecological footprint is the uniformity of bioproductivity of various types of lands, for example, forest land and cropland [34]. Thus, it provides only a general estimate of bioproductive land use.

This study emphasizes the environmental impact assessment of buildings located in tropical countries. The study is also significant for the policy makers because of very huge infrastructural enhancement, which will be required in the near future due to rapid urbanization. The study can be helpful to estimate the overall impact of the building sector in India. The natural resource stresses in India are high, and it has already exceeded the country's existing biocapacity. The total biocapacity deficit of the country is about 0.7 gha/capita [34]. A comprehensive assessment of the natural resource demand in the building sector can be facilitated by this study.

2. Methodology

A methodology has been developed that could assess the overall environmental impact of a building by considering resources such as materials, energy, emissions, water,

Table 1: Details of related EF equations and parameters.

Equations	Parameters	Constants
$EF_T = EF_{e\&m} + EF_t + EF_m + EF_{we} + EF_w + EF_{land}$	$EF_{e\&m}$ = EF of energy and building materials EF_t = EF of transportation EF_m = EF of manpower EF_{we} = EF of waste assimilation EF_w = EF of water use EF_{land} = EF of builtup/physical land	
$EF_{e\&m} = \left\{L_{CO_2}.\left(\frac{1-Aoc}{Af}\right)\right\}.e_{CO_2land} + \left(\sum \frac{C_{wood}}{Y_{wood}}\right).e_{forestland}$ $L_{CO_2} = M + \sum (E_c.\lambda_i) + (E_o.L_b)\lambda_{electricity} + \sum (E_d.\lambda_i)$	L_{CO_2} = emission during the lifespan of building M = materials total embodied CO_2 emission E_c = direct energy consumption (i.e., machinery used) during construction E_o = annual electrical energy consumption E_d = direct energy consumption during demolition L_b = building lifespan (i.e., assumed as 60 years) λ_i = emission factor of fuel (i.e., diesel fuel, electricity, etc.) C_{wood} = wood consumption in building Y_{wood} = yield of wood (i.e., 73 m^3/ha [39])	Emission factor of electricity ($\lambda_{electricity}$) is about 0.82 tCO_2/MWh [35] A_{oc} = percentage of CO_2 absorption in oceans (i.e., 30% [36]) A_f = CO_2 absorption factor of forests (i.e., 2.68 tCO_2/ha [37]) e_i = equivalence factor of different types of bioproductive land [38] (Table 4)
$EF_t = \left\{\left(\sum \frac{C_{mi}.D_{mi}}{T_c} + \sum \frac{C_{wj}.D_{wj}}{T_c}\right).E_{HDV}\right.$ $\left. +\sum \frac{M_k.D_{mk}}{T_b}.(E_{bus}.\lambda_{fuel}).\left(\frac{1-A_{oc}}{Af}\right).e_{CO_2land}\right.$	C_{mi} = consumption i^{th} material during a building lifespan (ton) D_{mi} = the transported average distance of i^{th} material C_{wj} = waste generation (ton) D_{wj} = transported average distance of j^{th} waste material M_k = number of labourers travelled by labourer D_{mk} = distance travelled by labourer T_c = the capacity (3.5 ton) of HDV T_b = the capacity (50 passengers) of bus λ_{fuel} = diesel emission factor (3.17 CO_2 kg/kg of diesel [40]) E_{HDV} = average fuel efficiency of HDV (0.222 kg of fuel/km [40]) E_{bus} = average fuel efficiency of bus (0.238 kg of fuel/km [40])	
$EF_m = \frac{d_w}{365}.f_d\left\{\sum \left(\frac{C_{fi}}{Y_{fi}}\right).e_i + \sum (C_{fuel_j}.\lambda_{fuel_j}).\frac{(1-A_{oc})}{A_f}.e_{CO_2land}\right\}$	d_w = total labour-days required during lifespan of building f_d = intake fraction of food that consumed during working (0.6) C_{fi} = food item consumption (kg/person) Y_{fi} = food item annual yield (kg/ha) C_{fuelj} = fuel used for food preparation (kg/person) λ_{fuelj} = fuel emission factor (tCO_2/kg of fuel)	
$EF_{we} = \sum \frac{C_{w_i}}{Y_{w_i}}.e_{landfill}$	C_{wi} = the amount of waste generated during building life (m^3) Y_{wi} = the yield of C&D waste disposal	
$EF_w = C_w\left\{E_w.\lambda_{fuel}.\frac{(1-A_{oc})}{A_f}\right\}e_{CO_2land}$	C_w = water use in building (m^3) E_w = energy required to uplift groundwater	
$EF_{land} = A_b.\ e_{built\ land}$	A_b = the total area of occupied land of building (ha)	

Table 2: Indian building construction details [41].

Type of construction	Unit	Brick (nos.)	Cement (kg)	Sand (m^3)	Aggregate (m^3)	Steel (kg)	Time required (day; 1 day = 8 hrs)
Brick work	m^3	494	95	0.2675			Labour-day 2.94
Reinforced cement concrete (RCC; M20 2% reinforced)	m^3		400	0.425	0.85	15.95	Labour-day 3.15 Concrete mixer 0.64 Vibrator 0.64
Cement plaster	m^2		8.6	0.024			Labour-day 0.3
Flooring	m^2		17	0.0178	0.0356		Labour-day 0.32 Concrete mixer 0.003

manpower, wastes, and so on. Simultaneously, some sustainable features have been examined that can reduce the ecological impact of buildings. In this case study, it computes the life cycle ecological footprint (EF_T) of a building, and its potential reduction is explained below:

2.1. Life Cycle Ecological Footprint (EF_T). The EF_T of a building takes into account the natural resource consumption, direct land use, transportation, manpower, and construction and demolition waste. In order to evaluate EF_T, the direct and indirect utilities in the building are transformed into their corresponding bioproductive land categories. The EF_T The system boundary of a building's lifespan is depicted in Figure 1. The principle of assessment of the EF_T is shown in Figure 2. The assessment of EF_T is calculated by the equation that is listed in Table 1. $EF_{e\&m}$, EF_t, EF_m, EF_{we}, EF_w, and EF_{land} represent the ecological footprint of energy and materials use, transportation, labour/manpower, waste assimilation, water use, and direct land use during the building lifespan, respectively. The all-listed parameters cumulatively assess the EF_T of a building.

2.1.1. Energy and Materials Use ($EF_{e\&m}$). The $EF_{e\&m}$ has been determined by the addition of the total energy-related emission and natural material used during the life cycle of a building. The $EF_{e\&m}$ of a building is calculated by using the equation that is provided in Table 1.

2.1.2. Transportation (EF_t). The EF_t of a building mainly depends on three factors: (1) building materials transportation, (2) waste transportation, and (3) manpower transportation. The assessment of the EF_t of building materials, labour/manpower, and C&D waste is completed by equations that are listed in Table 1. Some assumptions are considered to estimate the impact of transportation; it is based on the survey and data collection from the local construction industry.

The assumptions are as follows:

(1) Heavy-duty vehicles (HDV) are used to transport building materials and C&D waste
(2) Vehicle (i.e., HDV) capacity is about 3.5 tonnes, and the average distance covered is 10–15 km
(3) Labourers use diesel-fuelled buses (capacity of 50 passengers)
(4) Distance travelled by manpower is around 5–10 km

2.1.3. Labour/Manpower (EF_m). The manpower requirement during different types of construction work is shown in Table 2. The Central Public Works Department, Government of India [41] report, is used to estimate the total number of labour-day requirements during the building lifespan. In this study, the metabolic calories required are used to determine any construction activities by manpower [28]. Construction labour burnt approximately 1,400 metabolic kcal (i.e., the rate of 175 kcal/hr [42]) during one work-day (8 hrs.). It is 0.6 times the metabolic calories (i.e., 2,400 kcal/day of an Indian person [43]) burnt during the daily work-hours by labour. The main food items consumed in Indian conditions are presented in Table 3. The EF_m is determined by the equation that is provided in Table 1.

2.1.4. Waste Assimilation (EF_{we}). The C&D waste assimilation of a building is mainly depending on: (1) landfill disposal and (2) transportation. However, waste transportation is already included in Section 2.1.2. The EF_{we} is determined by the equation that is provided in Table 1.

2.1.5. Water Use (EF_w). Water use in the building during the life cycle (except for water used by occupants) is very essential nowadays because of the high water stress in the country. Groundwater is commonly used for building construction in India. In this study, the electricity consumed for uplifting underground water is considered to estimate the impact of water use. The EF_w of the building is determined by the equation that is mentioned in Table 1.

2.1.6. Direct Land Use (EF_{land}). This section emphasizes only the direct land occupied by a building. The EF_{land} of a building is determined by the equation that is provided in Table 1.

2.2. Measures for EF Reduction. Some possible measures are suggested in the section that may reduce the EF_T of the case building.

2.2.1. Sustainable Building Materials. Building construction materials are responsible for a significant amount of ecological impact on the planet [47, 48]. This section focuses on the assessment of environmental impact reduction of building by use of some selected sustainable materials. The

Table 3: Ecological footprint of food goods per capita in India.

	Monthly consumption [44]	Total annual consumption	CO_2 emission factor	Yield production [45, 46] (ton/ha)	EF (gha)
Vegetable	8.4 kg	100.8 kg		1.61	0.157
Pulses	0.90 kg	10.8 kg		0.69	0.039
Mutton	0.08 kg	0.96 kg		72	0.006
Beef	0.06 kg	0.72 kg		32	0.011
Cereals	9.28 kg	111.36 kg		2.39	0.117
Milk	5.4 litre	64.8 litre		458	0.062
Fish	0.252 kg	3.024 kg		0.035	0.030
Fruits	0.654 kg	7.848 kg		2330	1.58×10^{-6}
Edible oil	0.85 kg	10.2 kg		0.38	0.068
Wood	4.3 kg	51.6 kg	1.5–1.6 ($kgCO_2$/kg)	73 m^3/ha	0.028
LPG	1.9 kg	22.8 kg	3.31 ($kgCO_2$/kg)		0.025
Kerosene	0.40 litre	4.8 litre	2.58 ($kgCO_2$/litre)		0.004
Total annual EF/ capita					**0.549**

Table 4: Equivalence factor (e_i) of bioproductive lands [38].

Bioproductive lands	e_i (gha/ha)
CO_2 absorption land ($e_{\text{CO2 land}}$)	1.28
Forest land ($e_{\text{forest land}}$)	1.28
Crop land (e_{cropland})	2.52
Sea productive/marine land ($e_{\text{marine land}}$)	0.35
Builtup land ($e_{\text{builtup land}}$)	2.52
Pasture land ($e_{\text{pasture land}}$)	0.43

details of some selected sustainable materials are given in Table 5.

2.2.2. Renewable Energy Use. Renewable energy systems-solar, wind, geothermal, small hydro, and so on are generally considered a clean source of energy; however, it consumes some amount of energy (i.e., associated with materials, transportation, installation, etc.) and resources. It is accountable for the small amount of GHG emissions as well as bioproductive land consumption [55, 56]. In this study, a grid-connected rooftop solar photovoltaic (RSPV) system has been discussed. Various studies have been reported on the LCA of the different types of solar PV systems [57–60]. They suggest that the environmental impact of the solar PV system depends on various factors, which are listed as follows:

(i) Type of solar photovoltaic modules
(ii) Climatic conditions
(iii) Installation (grid-connected, stand-alone, ground- or rooftop-mounted, etc.)

The details of different types of modules and the balance of system of solar PV system are listed in Table 6.

3. Building Description

The case building is a government polytechnic building located in the city of Aurai, District Bhadohi, Uttar Pradesh, India. The construction (i.e., convention type) of the case study building was completed in the year 2011. The building's wall consists of fired clay brick (FCB) and mortar, and the building's roof is made of M20 grade concrete (Pozzolana Portland Cement (PPC)) with 2% reinforcement. The building's images are shown in Figures 3(a) and 3(b). The city of Aurai comes in the tropical climatic zone of India. The electricity consumption and constructional details (as obtained from the building site) are depicted in Table 7.

4. Results

The EF_T and their reduction potential assessment have been done for the case building. The obtained results are explained below.

4.1. Life Cycle Ecological Footprint (EF_T). The EF_T of the case building is calculated by summing all their components ($EF_{e\&m}$, EF_t, EF_m, EF_{we}, EF_w, and EF_{land}). The EF_T of the case building is 957.07 gha, while the annual average EF_T of the case building is 15.95 gha/yr (assuming the building's lifespan of 60 years). The EF_T per unit floor area of the building is 0.10 gha/m^2.

4.1.1. Energy and Materials ($EF_{e\&m}$). The total consumption of building materials and their EF have been obtained from Table 8. The building materials and resource usage during construction in India are taken from Table 2 in Annexure, which has been used in the study. Due to lack of data, maintenance (refurbishment) impact is assumed 6.4% [63] of the total building's life cycle impact in this study. Details of machinery use such as concrete mixer, electric pump, and electric vibrator are mentioned in Table 9. The $EF_{e\&m}$ of the case building as calculated by using the equation is 911.68 gha and their components (i.e., operational energy, building materials, construction energy, and demolition energy) have been shown in Figure 4.

Operational energy of the building contributes 52% share of the total $EF_{e\&m}$ of the building, while embodied energy of materials contributes about 47.5%. However, the combined environmental impact of the other two

Table 5: Details of selected sustainable building materials.

Building material	Bricks or blocks/m^3	Embodied energy	Emission factor#	Remarks
Fly ash brick (FAB; $230 \times 115 \times 75\,mm^3$)	600	1341 MJ/m^3 [49]	0.0778 tCO_2/m^3	Fly ash 60%, sand 30%, cement (lime + gypsum) 10%
Autoclaved aerated concrete block (AAC; $400 \times 200 \times 200\,mm^3$)	63	3.5 MJ/kg [50]	0.0002 tCO_2/kg	Light weight and low-density block
Hollow concrete block (HCB; $400 \times 200 \times 200\,mm^3$)	63	12.3–15 MJ/block [51]	0.00071–0.00087 tCO_2/block	
Limestone calcined clay cement (LC^3)	—	4,234 MJ/t [52]	0.245 tCO_2/t	Clinker 50%, calcined clay 30%, Limestone 15%, gypsum 5% [53]

#Indian primary energy to emission factor is 58 tCO_2/TJ [54].

Table 6: Embodied energy of different types of solar PV systems.

Components		Embodied energy (MJ_P/m^2 collector area)	Emission factor# (tCO_2/m^2 collector area))
Solar PV module	Mono-Si	2,860–3,860 [57, 61]	0.165–0.223
	Multi-Si	2,699–3,120 [57, 62]	0.156–0.181
	a-Si	710–1,990 [58, 63]	0.041–0.115
	CdTe	992–1,189 [59]	0.057–0.068
	CIS	1,069–1,684 [59, 60]	0.062–0.097
Balance of system (BOS)			
Inverter		503 MJ/kW_p [64]	0.029
Frame mild steel		32.24 (MJ_P/kg) [65]	0.0018
Installation		34 [64]	0.0019

#Indian primary energy to emission factor is 58 tCO_2/TJ [54].

(a) (b)

Figure 3: (a) Campus boundary (satellite view) and (b) image of the case building.

Table 7: Details of the case study building.

Building description	Unit	Value
Builtup land area	hectare	0.86
Total campus land area	hectare	3.2
Building electrical load	kW/phase	50/3 phase
Total student (the year of 2020)	Nos.	540
Annual electricity consumption	kWh	19,415 (from electricity bill)

components (i.e., EF of construction energy and demolition energy) of the $EF_{e\&m}$ is less than 1%. Figure 5 clearly shows that bricks contribute nearly half (52%) of the total material-related environmental impact (EF); while cement and steel account for 33.5% and 12.2% of the total material-related EF, respectively.

4.1.2. Transportation (EF_t). By using equation, the estimated EF_t of the building is 20.44 gha. Details of transportation vehicle capacity, fuel consumption, and emission factor of fuel are listed in Table 9.

4.1.3. Labour/Manpower (EF_m). Food intake by the construction labour has been considered to evaluate the EF_m of the case building. By using equation, the estimated EF_m of the case building is 20.85 gha. The environmental impact of labour/manpower for the case building is 2.2% of the EF_T of the building. Bioproductive land distribution in the EF_m of the building is shown in Figure 6.

Table 8: Details of materials consumed in the case study building.

Items	Total materials consumption	Embodied emission ($kgCO_2/kg$) [50]	EF (gha)
Cement	1,084,681 kg	0.61–0.74	133.9
Burnt clay brick	1,405,430 nos	0.162–0.195	207.8
Fine and coarse sand	2,653,239 kg	—	—
Aggregates	2,224,554 kg	0.0048	4.7
Steel	73,432 kg	1.74	48.8
Wood (teak India)	21 m^3	—	0.37
Marble stone	1.2 m^3	0.116	0.1
Ceramic tile	2.7 m^3	0.74	1.4
Paint	0.81 ton	0.36 $kgCO_2/m^2$	0.1
PVC pipe	1.85 ton	2.56	1.6
Glass (common)	0.732 m^3	0.86	0.47

Table 9: Construction machinery use in the case building.

Machineries	Capacity	Energy rate	α_{fuel} ($kgCO_2$/unit input) [40]	Ecological footprint
Concrete mixer	5 hp	1.6 litre/hr	3.17 CO_2 kg/kg diesel	1.43×10^{-03} gha/hr
Water pump	1 hp	0.745 kWh/hr	0.82 tCO_2/MWh	2.93×10^{-04} gha/hr
Heavy-duty truck	3.5 t	0.240 kg/km	3.17 CO_2 kg/kg diesel	7.21×10^{-05} gha/t-km
Bus	50 persons	0.238 kg/km	3.17 CO_2 kg/kg diesel	5.0×10^{-05} gha/person
Electrical vibrator	1 hp	0.745 kWh/hr	0.82 tCO_2/MWh	2.93×10^{-04} gha/hr

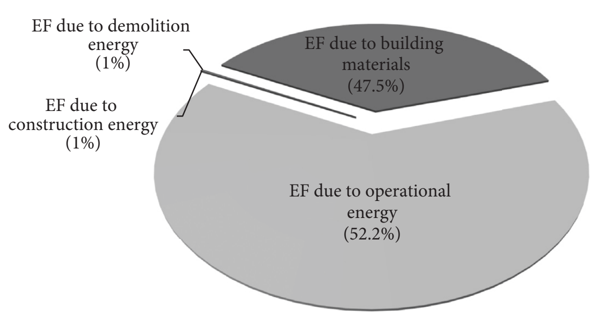

Figure 4: Fraction of the $EF_{e\&m}$ of the case building.

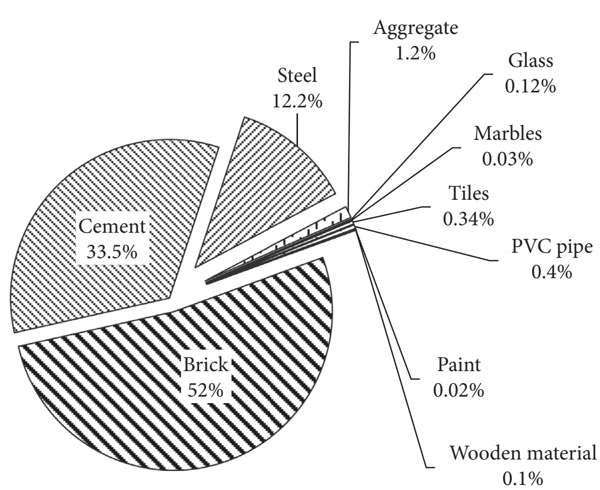

Figure 5: The environmental impact (EF) of materials consumed in the case building.

4.1.4. Waste Assimilation (EF_{we}). Waste generated during the different life phases is calculated according to Table 10 in Annexure. EF impact of waste generation may be reduced through recycling/reuse, but it is not evaluated in this study. By using equation, the estimated EF_{we} of the case building is 18.2 gha (i.e., nearly 2% of the EF_T).

4.1.5. Water Use (EF_w). Water consumption is mostly involved in the construction phase of the building (27 kilolitres of water per m^2 floor area [17]). The construction phase is more dominating than the other phase of building in terms of water use because refurbishment (during operation phase) and demolition (end of life) use a comparatively low amount of water. Therefore, water consumed during the maintenance and demolition phases has been neglected in this study. The EF_w is about 11.38 gha for the building (i.e., 1.2% of the EF_T).

4.1.6. Direct Land Use (EF_{land}). By using equation, the estimated EF_{land} of the case building is about 8 gha (i.e., 0.84% of the EF_T).

The bioproductive lands contribution is depicted in Table 11 and the percentage fraction is depicted in Figure 7. The significant land type involved in the EF_T is CO_2 absorption land (i.e., 95.25% of the total bioproductive land) because the case building consumed direct and indirect energy during the lifespan. In EF analysis, all the energy consumption and emissions are represented in CO_2 absorption land. The EF_T distribution of different life cycle phases of the building is shown in Table 12. It clearly represents that the environmental impact of the construction and operation phases are 49.78% and 47.90% of the total impact of the building, respectively. In general, the operation phase is more dominant compared to the rest of the life phases in terms of energy use [12]. However, in the case study building, the embodied impact is almost half of the buildings' overall impact. It is because the building is not equipped with any HVAC systems. The electricity

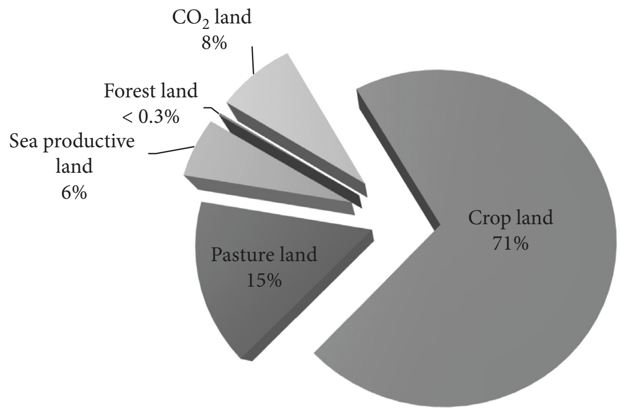

Figure 6: The percentage distribution of bioproductive land consumed in the EF_m.

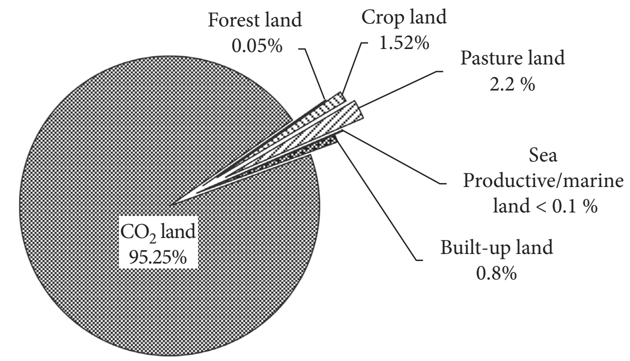

Figure 7: Involvement of different bioproductive lands during the building lifespan.

Table 10: C&D waste generation during life phases of typical Indian building.

Life phase	Unit	Value [15]
Construction waste	kg/m^2	40–60
Maintenance waste	kg/m^2	40–50
Demolition waste		
Semi-pucca	kg/m^2	300
Pucca	kg/m^2	500

consumption is very low during building operation, mainly meant for lights and fans. Therefore, operational environmental impact is nearly equal to the embodied environmental impact of the building (see Table 12).

4.2. Reduction Potential in EF_T. Reduction potential in the EF_T of the case building is estimated in two ways: first, sustainable building materials, and second, renewable power (solar PV) system.

4.2.1. Sustainable Building Materials. The EF_T reduction potential of the case building by use of different sustainable materials and their combinations has been assessed in this section. For such estimation, the required material properties are taken from Table 5. The estimated value of the EF_T by using alternative materials (individually or in combination) in the building is shown in Figure 8. The EF_T of the building may reduce up to 22.2% (Table 13) if construction materials such as fired clay brick (FCB) and Portland Pozzolana cement (PPC) are replaced with sustainable materials (i.e., FAB, HCB, AAC, and LC^3). Husain and Prakash reported the constructional EF of the FAB consist wall as nearly 50% lower than the conventional wall (i.e., consisting of FCB) [66]. The ecological footprint of FCB, FAB, HCB, AAC, PPC, and LC^3 is calculated as 0.001 gha/brick, 0.00004 gha/brick, 0.0002 gha/block, 0.0006 gha/block, 0.00009 gha/kg, and 0.00006 gha/kg, respectively.

4.2.2. Renewable System. The database of RETScreen software is used to assess the capacity of five different types of PV module systems that can meet the annual electricity demand of the building (Table 14).

The life cycle ecological footprint of solar PV modules (tropical climatic zone) is shown in Figure 9. The thin film (i.e., a-Si, CdTe, and CIS) solar PV modules have comparatively lower EF values than mono-Si and multi-Si modules. However, the thin film-based PV module systems are not used for large-scale power production because of their low efficiency and high degradation rate. In India, multi-Si PV modules are generally used for power production. The average life cycle EF of mono-Si, multi-Si, a-Si, CdTe, and CIS-based solar PV systems were evaluated as 0.0694, 0.0605, 0.0297, 0.0250, and 0.0305 gha/m^2, respectively. In Table 14, the electricity generation from the different types of modules is $0.56–2.65 \times 10^{-5}$ gha/kWh. In India, the emission factor of grid electricity is about 0.82 tCO_2/MWh [35], and the estimated EF of grid electricity is 2.72×10^{-4} gha/kWh while ignoring factors other than emissions. Hence, the EF reduction potential by the solar PV systems is in the range of 10 folds to 50 folds.

The potential reductions of the EF_T through the different solar PV systems are shown in Figure 10. The grid-connected rooftop solar PV systems can probably reduce the EF_T in the range of 507.6–519.7 gha (i.e., 45.76–47% of the existing building). The maximum reduction in the EF_T has been estimated for CdTe modules; it is because of the lowest EF of such modules.

4.3. Combined Effect of Building Materials and Renewable Systems. If both the reduction measures are incorporated simultaneously into the building, it has the potential to reduce the EF_T by up to 69% of the existing building. EF_T with all possible combinations of building materials and solar PV modules is depicted in Table 15. The lowest EF_T of the case building has been estimated for the combination of HCB + LC^3+CdTe (i.e., 295 gha). Due to the material constraints, hazardous waste disposal, and high degradation rate of the thin film module; the multi-Si-based systems have the largest market share in the world (i.e., 51% of the total installed capacity) [67]. Therefore, the combination of HCB + LC^3+multi-Si is best suited for the building in the Indian context.

Table 11: Breakup of different bioproductive lands in the EF_T.

	Land category (gha)						
	CO_2 land	Crop land	Pasture land	Forest land	Sea-productive land	Builtup	Total (gha)
$EF_{e\&m}$	877.74			0.39			878.13
EF_w	11.38						11.38
EF_m	2.12	14.50	2.98	0.11	1.15		20.85
EF_{we}			18.20				18.20
EF_t	20.44						20.44
EF_{land}						8.06	8.06
EF_T							**957.07**

Table 12: The EF_T distribution of the building.

Building phases	Land category (gha)							
	CO_2 land	Crop land	Pasture land	Forest land	Sea productive land	Builtup land	Total (gha)	Percentage distribution
Construction	446.88	14.30	5.53	0.50	1.13	8.06	476.40	49.78%
Operational	458.48						458.48	47.90%
Demolition	6.32	0.21	15.65	0.0015	0.02		22.20	2.32%
EF_T							**957.07**	100%

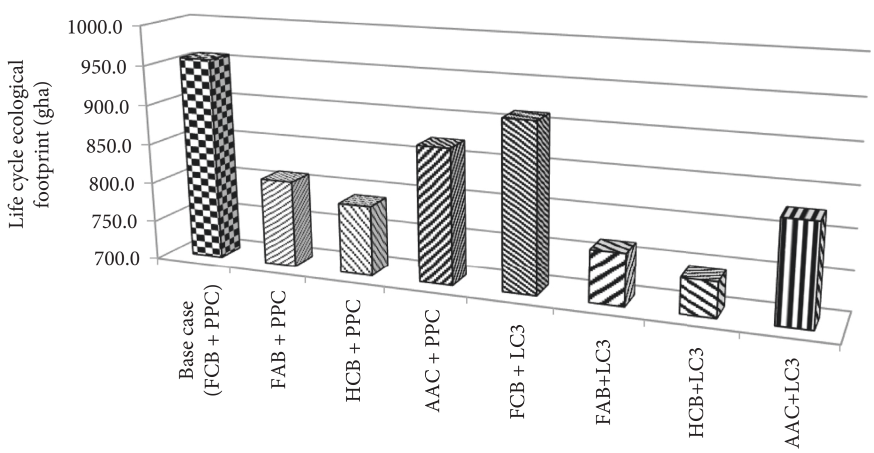

Figure 8: The EF_T of campus building based of different construction materials.

Table 13: The EF_T of the building by used on different construction material.

Main building envelope material	EF_T of the building (gha)	EF_T per m^2 floor area (gha/m^2)	Percentage reduction potential in the EF_T
Base case			
FCB + PPC	957.07	0.105	—
Proposed case			
FAB + PPC	810.21	0.089	15.3%
HCB + PPC	789.19	0.086	17.5%
AAC + PPC	871.19	0.095	9.0%
FCB + LC^3	912.30	0.100	4.7%
FAB + LC^3	765.44	0.084	20%
HCB + LC^3	744.42	0.081	22.2%
AAC + LC^3	826.43	0.090	13.6%

Energy-efficient retrofitting in buildings has great potential to reduce GHG emissions [68, 69]. For tropical climatic buildings, green roof designs and reflective roofs (reflective coatings on roof surface) can be installed to reduce the ecological footprint of the building [47, 66]. Solar tubes for daylighting can significantly reduce the artificial lighting demand of a building and may also reduce the building's ecological footprint. Hence, the ecological footprint can be reduced by using additional sustainable measures in buildings.

Table 14: EF assessment of different types of module-based PV systems for the case building.

Type of module	PV system capacity (kW)	Panel collector area (m^2)	Life cycle electricity generation (gha/kWh; x 10^{-5})	Life cycle EF of PV system (gha/kW)	Life cycle EF of PV system to meet building demands (gha)
Mono-Si	12.4–12.6	68–154	1.05–2.65	0.325–0.816	4.1–10.3
Multi-Si	12.5–12.7	78–181	1.12–2.35	0.353–0.884	4.4–11.1
a-Si	11.66–11.76	180–222	0.56–2.41	0.185–0.798	2.2–9.4
CdTe	12.06–12.11	96–140	0.57–0.97	0.183–0.314	2.2–3.8
CIS	12.75–12.81	115–194	0.72–1.82	0.219–0.553	2.8–7.1

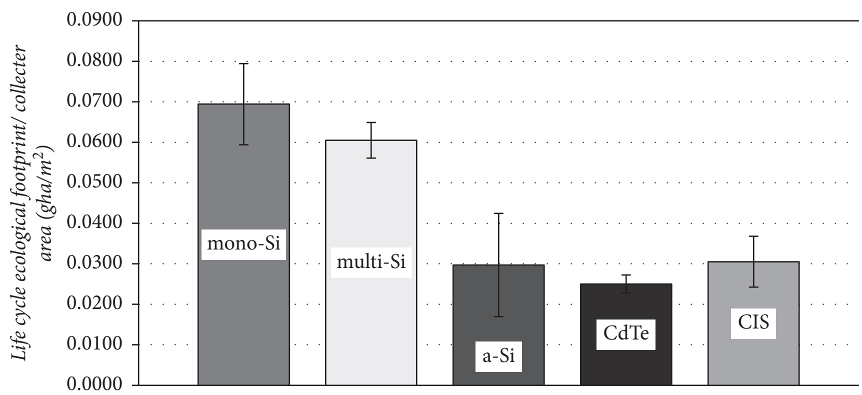

Figure 9: The life cycle EF of different PV module systems per m^2 collective area.

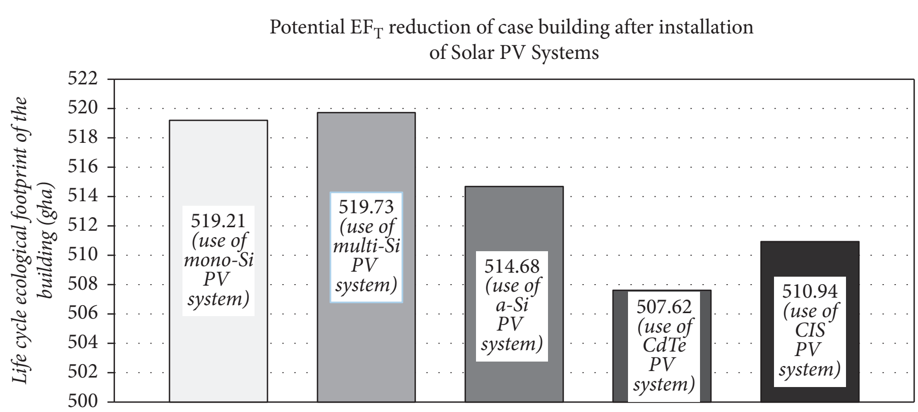

Figure 10: The EF_T of building with different types of PV modules system installation.

Table 15: The combined effect of materials and rooftop solar PV system on the EF_T (gha).

Power supply	Materials							
	Base case (FCB + PPC)	FAB + PPC	HCB + PPC	AAC + PPC	FCB + LC^3	FAB + LC^3	HCB + LC^3	AAC + LC^3
Grid electricity	957.07	810.2	789.2	871.2	912.3	765.4	744.4	826.4
Mono-Si	519.2	372.3	351.3	433.3	474.4	327.6	306.6	388.6
Multi-Si	519.7	372.9	351.9	433.9	475.0	328.1	**307.1**	389.1
a-Si	514.7	367.8	346.8	428.8	469.9	323.1	302.0	384.0
CdTe	507.6	360.8	339.7	421.7	462.8	316.0	295.0	377.0
CIS	510.9	364.1	343.1	425.1	466.2	319.3	298.3	380.3

5. Conclusions

This study focuses on assessing the life cycle ecological footprint of the case building. The proposed methodology may help estimate the building impact as well as restrict to use of resources within the planetary limit. Two important measures have been investigated for the reduction in EF_T of the building, that is, the use of sustainable materials and renewable power (solar PV) system. These two measures provide a significant reduction (maximum 69%) in EF_T for the building examined. With the installation of rooftop solar PV alone, the EF_T reduces by 47%.

The EF_T of the case building is about 957 gha (for 60 years of building life). The annual average ecological footprint of the case building is 15.95 gha, and the EF_T per m^2 floor area of the building is 0.10 gha/m^2. The major contributor to the EF_T of the building is CO_2 land that is 95.25% of the total bioproductive land needed for the building.

Such a comparison shows that EF for the built environment varies with regard to architectural and constructional features, climatic conditions, level of thermal comfort, and so on. Hence, a local assessment of EF is important in order to execute strategies for EF reduction.

Abbreviations

AAC: Autoclaved aerated concrete block
A_f: CO_2 absorption factor of forests
A_{oc}: Percentage of CO_2 absorption in oceans
C&D: Construction and demolition
EF: Ecological footprint
e_i: Equivalence factor of bioproductive land
FAB: Fly ash brick
FCB: Fired clay brick
GHG: Greenhouse gas
HCB: Hollow concrete block
HDV: Heavy-duty vehicle
LC^3: Limestone calcined clay cement
LCA: Life cycle assessment
LCE: Life cycle energy
PPC: Pozzolana portland cement
PV: Photovoltaic.

Data Availability

All the data used in this research work are cited in the manuscript.

Disclosure

This is an extended version of the following source: "https://novapublishers.com/shop/ecological-footprints-management-reduction-and environmental-impacts/."

Conflicts of Interest

The authors declare no conflicts of interest.

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