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Original Research Article

Improving the Buildings' Sustainability through Combined Matrix Assessment of Embodied Energy, Water, and Carbon: Case of Conventional Houses, Jammu – India

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ABSTRACT

The study compares embodied energy, water, and carbon parameters in the cradle-to-gate construction phase for conventional houses in Jammu, India. Besides relying on hybrid material coefficients and field investigations-based materials database, the study adopts a general life cycle assessment framework. Descriptive statistics and regression techniques aid in meeting the findings. A strong interrelation exists between embodied energy and carbon, but a considerably weak embodied water-to-energy or embodied water-to-carbon relationship emerges. The top embodied energy and carbon-impacting materials (like brick) retard significantly in embodied water impacts. At the same time, steel deserves less attention than sand, aggregates, and cement, considering all three parameters together. Therefore, a new dimension to appropriately using building materials and construction technologies looms by outlining a broad materials palette. The results call for a differing embodied water optimisation approach to embodied energy or carbon-pertaining ones. The construction players receive a new insight towards a sustainable building approach.

KEYWORDS

Embodied energy, Embodied water, Embodied carbon, Sustainable buildings, Energy-water-carbon nexus, EPiC database.

INTRODUCTION

The quest for rational energy use and related environmental impacts has been visible for at least three decades. However, the freshwater crisis is also among the top agendas in the current world order. Many building rating systems and sustainable development goals (SDGs) are associated with optimising energy or water consumption, given the fact that one-third of greenhouse gas (GHG) emissions [1] and 50% of energy [2] consumed globally are attributed to buildings, their environmental impacts need serious checks. Attention is also required because buildings consume 16% of worldwide water [3]. So, the sustainability concept owes a lot to the global construction industry. Proponents realise the link of water, energy and carbon

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emissions towards regional sustainable development of freshwater availability, energy security and global warming mitigation [4]. Indeed, the comprehension of the water-energy-carbon link nudges the policymakers for socio-economic sustainability [5]. Besides energy priority for decades, water use in various activities, including construction, has started to seek attention. Construction is the most water-consuming sector after agriculture [6], and the Indian construction sector is perhaps the largest globally [7]. India needs to catch up in water and land resources and, hence, the energy to cater for a staggering 17% of the global population proportion [8]. The Indian construction sector accounts for 30% of the total country's CO_2 (GHG) emissions and 40% of energy consumption [9]. Conventional Indian houses are unsustainable and represent irresponsible resource consumption [10]. A sustainable building relies on less water and energy, emits fewer greenhouse gases (GHG), and uses materials more efficiently, while waste production is efficient for conventional buildings' LC [11]. The established research on embodied energy (*EE*) in buildings has helped to have more energy-efficient buildings in recent years [12]. The strong relationship of *EE* with carbon emissions [13] means that carbon emissions from building construction have also been mitigated to a specific effect. However, simultaneous checks on embodied water (*EW*) parameters still need to be present in previous attempts, and the holistic Sustainable Built Environment (SBE) that is envisioned needs to be improved [14]. The scientific community is looking back at vernacular architecture to conserve water consumption in building construction [15]. The time has come to consider drinking water consumption assessment and reduction due to on-site construction personnel [16]. So, introspection in Indian houses involving *EW* parameters alongside conventionally taken *EE* or carbon emissions towards SBE is worthy.

Previous research

The water embodied in materials through production, extraction and manufacturing of materials is known as indirect virtual water (VW) or materials embodied water (*EW*) [17]. Water footprint (WF) assessment, in addition, includes green water (stored in plants and soil) and grey water (polluted water). Stand-out Indian [18] or the Australian studies of 2004 [19], 2007 [20] and 2011 [21], along with a few other global studies from Spain [22] and Iran [23], reveal that VW or blue WF or total *EW* terms are inter-changeable, with supportive system boundary definition. Australia kickstarted the *EW* research in 2004. The first Indian study by Bardhan [17] and her follow-up investigation in 2016 [24], alongside a hotel-based Indian case [25] and the much-improvised 2022 Indian study [10], computed *EW*, including direct water, in the range of 16.27−27.6 kL/m^2. Primarily, concrete and steel are *EW*-intensive materials [26]. Indian constructions are high on *EW* [14]. *EW* studies require enhanced explorations to contribute to environmental sustainability and water scarcity [22].

Like water, energy use in the building is attributed for almost its entire life till demolition. It is similarly composed of direct and indirect energy, as in *EW* definitions [27]. On a similar pattern, embodied carbon (*EC*) relates to material consumption, construction, and operational phases besides the demolition stage of building LC. Materials production mainly contributes to *EE* and GHG (*EC*) [28]. The phase of 2000−2017 sees a rapid increase in dwellings' floor area but a minimal reduction in materials energy intensity [29]. Starting from the 2003 situation [30], Indian studies by Ramesh *et al.* [31], Shukla *et al.* [32], and the 2021 investigation by Vengala *et al.* [33] find *EE* in the 1610−7350 MJ/m^2 range for different buildings and raise the bar of local manufacturing, materials, and construction techniques in optimising *EE*. The 13.9 GJ/m^2 value shows the *EE*-intensive nature of UAE constructions in a study [34] based on the Australian EPiC database and material quantities to report initial *EE* (including the construction phase). *EE* predominantly contributes to LC energy; however, construction technologies and building materials innovations report EE cutting up to 62% [35]. Massively increasing Indian building stock accounts for 40% of the country's electrical energy consumption [36]. A 2022 study emphasises the role of innovative construction practices for net zero buildings besides achieving SDGs through operational energy (OE) and emissions reduction [37].

Environment impacts, or energy issues of construction, are vastly covered in the research compared to *EW* [38]. A cradle-to-grave LCA study in Spain finds that the construction/renovation stage (60%) and use phase (40%) of residential buildings are environmentally impacting [39]. Including water consumed in electricity production is advocated in assessing buildings *EW* [40]. Bringing more renewables through international collaborations of wind-solar energy is a consolidating hope [41]. Table 1 highlights most of the existing scientific contributions specific to the construction sector at the building scale or urban level, highlighting interrelationships among two or all three of *EW*, *EE*, or *EC* parameters.

Table 1. Construction sector-specific studies covering *EW-EE* or *EW-EE-EC* nexus

Country of study (Year)	Source	Parameters	Methodology/Remarks
Spain (2022)	[48]	*EW, EC*	Research survey, environmental, and economic data. Sustainability decision-making (reducing *EC, EW*) is achieved by identifying and adjusting impacting building materials and machinery.
Australia (2022)	[49]	*EW, EE, EC*	QGIS. Direct interrelationship between the three parameters. Diverse residential constructions and efficient materials are required.
USA (2023)	[40]	*EW, EE*	I-O method. 2.5%−31.2% in the share of EREW in total *EW* of construction materials. *EW* vis-à-vis energy use is vital towards achieving a truly sustainable built environment.
India (2024)	[50]	*EW, EE*	Site-based. Global databases are fine for initiating *EW* studies, irrespective of regional contexts. Quantifications may differ depending on the database use; however, the chronology of top impacts remains similar. *EW* and *EE* have an inverse relationship concerning material consumption scenarios in conventional Indian houses. An *EW* conserving approach can also be a fitting *EE* solution if a material is thoughtfully selected during the design phase.
USA (2022)	[42]	*EW, EE*	I-O-based hybrid method. *EW* and *EE* are weakly correlated, but EREW and *EE* are strongly correlated. An energy-carbon-water nexus perspective is required, rather than an energy component in isolation, to see the environmental impacts of construction.
UK (2021)	[14]	*EW, EE, EC*	I-O methodology. There is no correlation between the water footprint and the construction sector's energy or carbon footprints.
USA (2023)	[44, 51]	*EW, EE, EC*	A macro-economic model based on I-O methodology. The *EE* is near perfect and positively correlated with *EW*. A decrease in *EE* use may not help decrease the majority of *EW*. Saving just *EE* may only help conserve 13%−16% of *EW*. Buildings' environmental embodied impacts should be assessed through the energy-carbon-water nexus perspective.
India (2016)	[52]	*EW*	Experiment based. A significant *EW* saving but not so much *EE* or carbon emissions saving by using gypsum plaster concerning conventional sand-cement plaster. So, *EW* and *EE* are not strongly correlated.
Iran (2019)	[23]	*EW*	Process-based LCA. Construction-specific VW supply and consumption involves the dominant share of energy and GHG emissions. The *EW*−*EE* relationship still needs more concrete evidence.
Saudi Arabia (2019)	[53]	*EW*	Overview study. Popular concepts-green and zero-energy buildings strive to save water and energy. Architects, town planners, and engineers must consider combining *EW* and *EE* in new buildings.
Spain (2018)	[54]	Energy, water, and carbon	LCA method. The operation and maintenance building phase is covered. Renewable heating and lighting are emphasised in recommendations towards decreasing the environmental impacts of case buildings.

As Table 1 outlines, a fragile *EE*−*EW* relationship [42], while a positive *EE*− *EC* (GHG) emission relationship is preliminary predicted [13]. A USA research team performed several scientific investigations based on the I-O model in 2022−2024 [42-44], highlighting the positive correlation between *EE* and *EW* while meticulously highlighting that energy-specific measures do not considerably control EW. The matter of energy-water dependency deserves profound insight due to feeble evidence [23]. The inter-dependency of *EW* and *EE* is anticipated, and the energy-water nexus perspective is crucial to evaluating resource consumption and the environmental impacts of buildings [42]. A total void exists in Indian-specific studies. An Indian scholar [45] sees the worth of energy-water linkage in building regulations and fewer regulations dealing with the operational phase of buildings. Non-compliance with building regulations is common [46], especially for conventional Indian stand-alone houses [10]. A construction sector-specific study [14] involving many developed and developing economies finds no notable correlation between water, energy and (GHG) carbon dioxide (CO_2) footprints but hints at an energy-CO_2 correlation. An Indian study [47] covering cradle-to-site finds a 90% share in buildings' carbon footprint due to cement, brick, and steel, with cement alone contributing 60%. It finds high relevance of materials embodied energy for the carbon footprint of buildings and calls for pertinent material selection in the design phase.

Prolonged ignorance towards significant water impacts in construction exists due to increased focus on energy or CO_2 (GHG) only. A city-level nexus-based review study [4] finds increased significance in the 'energy-water' nexus approach rather than including carbon. While the proponents [65, 56] argue for a combined consideration of *EE* and *EW* for buildings, studies must indicate the *EW*, *EC*, and *EE* relationship at the building level [44]. A study [54] involving two school buildings seeks energy, water, and carbon footprints in Spain. However, the operation and maintenance phase is included rather than embodied. Studies by USA scholars [44, 51] seek *EC*, *EE* and *EW* assessment for four university buildings based on the I-O model of a developed economy of the USA. The same scholars advance to intervene in the Architecture plus design (A+D) of urban buildings through the impact of surface aspect ratio on the three embodied parameters, using software modelling and I-O data [56]. It emerges as a solitary effort at the building level to seek sustainable building solutions based on the nexus of the three embodied parameters. So, the current endeavour is a worthy attempt to build *EC*, *EE*, and *EW* relationships for four conventional house constructions.

Not only Indian [10, 17] or US studies [57, 58] but also the proponents from other global locations [21, 59, 60] recommend using hybrid LCA methods owing to complexity and overestimation in the I-O method or underestimation in the process-based LCA method. Given the unreliability of input-output (I-O) methods in the current world order, precisely for developing economies like India, the process-based computations are more appropriate, provided the system boundary is robust. The absence of Indian-specific databases for unit material consumption, specifically for *EW*, nudges the use of established global databases. Relying on materials inventory is logical [17] and aligned with the universal database [34]. So, the literature encourages unravelling *EW*, *EC* (GHG), and *EE* relationships employing a process-based hybrid methodology.

The current study assesses *EW*, *EC* (GHG) and *EE* for four conventional houses in Jammu city, India, due to building material consumption covering cradle to gate (of production plant) stage only. The study uses the alone comprehensive database, i.e., the environmental performance in construction (EPiC) database, providing material-wise coefficients simultaneously for *EW*, *EE*, and *EC* (GHG) [61]. The authors of [34, 50] support the universal applicability of databases like EPiC for missing contextual databases or, in case precise construction procedures (like green rating requirements) are absent. The precise material inventory availability coupled with re-verification through field measurements and on-site visits are compulsory attributes behind the selection of the houses. Further, the cross-sectional technique is chosen to ensure near similarity in construction year and location of the case houses (to eliminate external agencies, if any) and define the conventional construction set-up of the location. The standard methodology recommended by ISO 14044 [62] or 14046 [63] LCA frameworks (**Figure 1**) is adhered to predict the house-wise impacts (disaggregated cases) and combined one (aggregated case). The current study is the first building-specific attempt to outline *EW-EE-EC* comparatives simultaneously and positively impact 2030 SDGs.

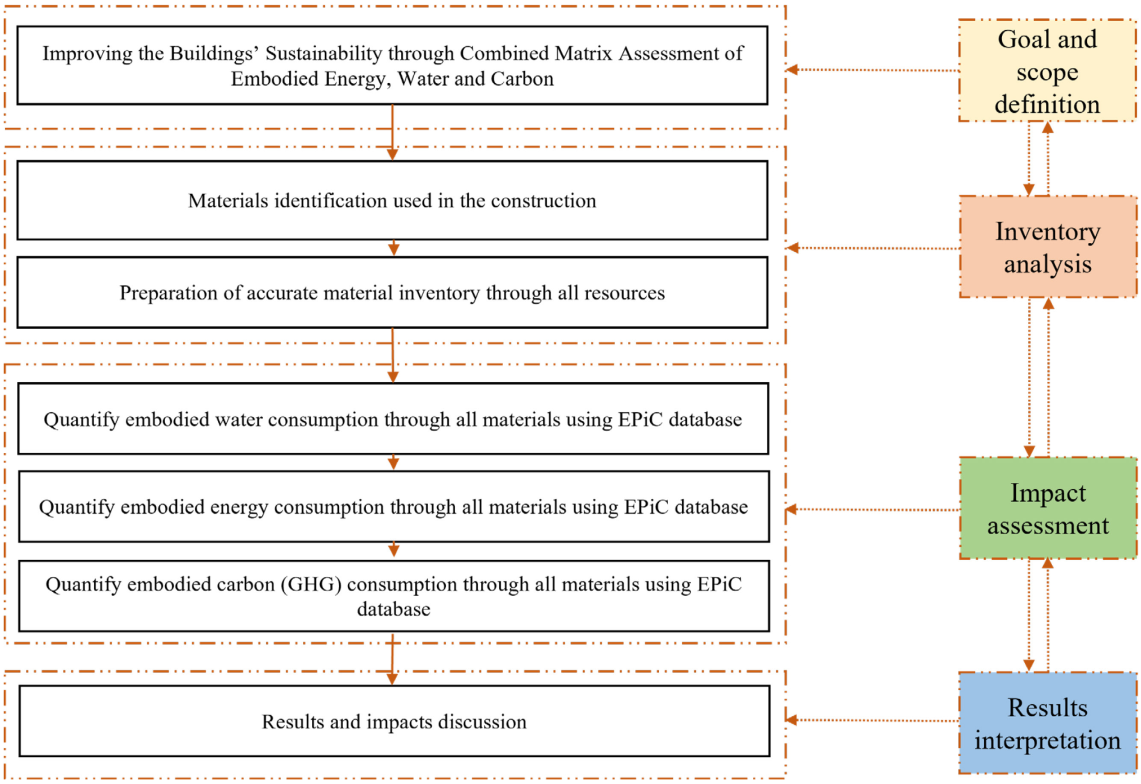

Figure 1. Methodology adopted in the study

Study area

The study location chosen is Jammu City in the union territory of Jammu and Kashmir (J&K), India. **Table 2** details the essential modalities of the four houses (herein referred to as CR-1, CR-2, CR-3, and CR-4) to encapsulate the relevant leads. Individual houses taken in isolation are called disaggregated cases, while all houses taken together are termed aggregated cases (CR-T).

Table 2. Description of the conventional houses under study: CR-1, CR-2, CR-3, and CR-4 are four contemporary residences (CR) chosen in the study

Description	CR-1	CR-2	CR-3	CR-4
Plot area [m^2]	500	250	125	250
Total construction area [m^2]	350	391	107	380
Number of floors	2	2	1	2
Project completion year	2022	2022	2021	2022
Is the cellar present?	No			
Building type	Stand-alone family house (plotted accommodation)			
Location	Jammu			
Ownership	Self-owned (family)			
Concrete mixing	In-situ			
Type of structure	RCC frame		Composite (few RCC columns with load-bearing brick walls)	

Jammu, a northern Indian city, has excellent potential for development after Article 370 abrogation in 2019. The city's location and connectivity add to its potential to invite record development. The peripheral conventional houses forming the sprawling growth of the city are already reckoning. Conventional houses are generally single or two stories high and use brick walls with RCC roofs. Specialised construction procedures like green building norms are far from practice. Also, construction is typically driven by owner-contractor consensus concerning materials in structure and finishing works. The conventional architecture of the city is already debatable [64], while a neighbouring but smaller city − Katra, is urging for redevelopment owing to urbanisation [65]. Though modern vertical cities have pros and cons [66], Jammu will likely continue embracing low-rise house typologies for some time, given its seismic, socio-economic, topography and urban morphology considerations.

The state of Jammu and Kashmir, especially the Kashmir zone, has interesting vernacular buildings in wood but is covered in literature to a lesser extent [67]. Traditional architecture is losing its identity through globalisation and monotonous construction preferences [64]. Interestingly, studies seeking traditional and contextualisation of future developments [68] and contemplating potential alternate energy use [69] for Katra exist, but Jammu needs to be addressed as such. Brick manufacturing is available but is relatively informal with quality concerns. Sand and other aggregates used to be available in plenty through the Tawi River, but enormous constructions involved its exploitation and further strictness by the local administration. The city receives satisfactory rainfall but is less aware of techniques like rainwater tanks [70]. Due to the considerable slopy terrain of the city, rainwater ends in mere wastage. Previous research predicts high *EW* [10] and *EE* [35] consumption of such conventional houses in Jammu. The study involves four conventional houses in the old Jammu City expansions per Table 2 details.

MATERIALS AND METHODS

The study proceeds with a set aim by merging various processes and techniques described below.

The goal of the study

The study aims to improve the buildings' sustainability through a combined matrix assessment of embodied energy, water, and carbon for conventional house constructions in the Indian context.

The research novelty and implications are:

- The *EC*, *EE* and *EW* assessments are a rare phenomenon to date.
- The comparative *EW*, *EE*, and *EC* assessment nudges in construction and A+D phase decision-making towards better sustainable built environments.
- Inevitable evidence shown − whether the prevalent energy or carbon-conscious approaches are also worthy of controlling embodied water. Recommendations and solutions for alternatives, if any, constitute the outlined impact of this research.
- The fact is that conventional houses are the largest typology by proportion in Indian constructions. So, such a selection of the building typology is fitting to envision sustainable built environments.
- The exploration is a much-needed contribution to outline not only the scarce *EW* domain but also a way to address it. The established *EE* domain is further incremented, and a new dimension towards achieving 2030 SDGs is therefore inevitable.
- The fact that the outcomes empower policymakers and people, alongside building professionals, towards the shared and distributed responsibilities for sustainable conventional houses, the study is impacting society.
- The advanced study considers an inventory of 18 materials (15 material groups) instead of only brick, steel, and cement.

Methods

The research carries on the methodology under a joint preview of ISO 14044 [62] and ISO 14046 [63] frameworks as per Figure 1. As evident in this figure, the entire research methodology encompasses goal and scope identification, inventory analysis, impact assessment, and results interpretation and stands covered in dedicated sections accordingly. The stand-out results are summarised in the conclusions section.

Scope and limitations of the study

The study carries for the material production phase in acronym to the cradle-to-gate (of the plant) stage only. The study trusts the near-uniform production process of maximum materials globally. Thus, the study relies on the material inventory as the standard parameter to predict *EC*, *EE*, and *EW* and uses the singular database. Multiple databases, houses of different contexts, or buildings with different typologies are not considered to eliminate overriding parameters like context, climate, construction controls, and other user/owner-specific parameters. The availability of only one database for *EW*, *EC*, and *EE* and covering only the cradle-to-gate phase also encourages the disqualification of other LCA phases for the intended comparative assessments of the three parameters. The study is limited to the conventional houses of fast-developing Jammu city and carefully selected through the cross-sectional technique to gauge the study's intended purpose effectively. Unit material-wise consumptions are referred to through consultation of hybrid embodied coefficients. Such coefficients cover the entire complexities of production processes (direct and indirect consumptions), including the upstream impacts. So, the various production processes required to meet the process-based hybrid methodology are covered by adopting hybrid embodied coefficients of the EPiC database.

Study boundary

The study undertakes the material production phase, as illustrated in Figure 2. As this figure expresses, all the processes and stages until the material production (gate of production plant) are the thorough system boundary ingredients. As already discussed, the comprehensive production phase, including the complexity of upstream impacts, is covered by referencing hybrid embodied coefficients of the EPiC database. Figure 2 also clarifies the omissions of the LC phases from the system boundary.

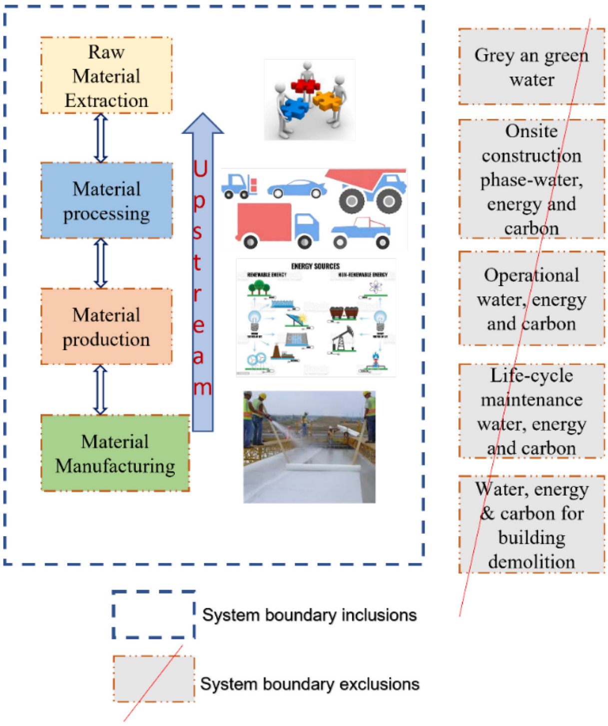

Figure 2. Study boundary details

Tools and techniques

The study uses the following tools and techniques:

- ISO 14044 and ISO 14046 LCA framework to methodologically process the research.
- Cross-sectional technique to select the houses. Selected houses are typical conventional houses. Besides, they correlate in materials, height, construction technique, and external agencies (like climate), which is crucial for this study as they bear almost similar contexts of location and year of construction.
- The process-based hybrid LC analysis approach employing the hybrid embodied coefficients for material consumption.
- The EPiC database used because it is the only global database providing *EC*, *EE*, and *EW* consumptions per unit of material production.
- Site visits and field-based records supported by on-site investigations to deduce precise material inventory; inventory precision is the basis for selecting cases.
- Descriptive statistics to compute disaggregated and aggregated impacts, utilising material inventory and EPiC database.
- System boundary analysis at length to gauge disaggregated and aggregated cases and material-wise consumptions.
- Statistical modelling based on regression technique to unravel the inter-relationship between *EC*, *EE*, and *EW*

Inventory analysis

The material consumption quantities and respective hybrid embodied coefficients are essential to compute for inventory analysis. The inventory for each disaggregated case is arrived at via field investigations coupled with on-site records available.

The material inventory is available in conventional site units for most of the materials. Such quantities are converted into the same units through standard conversion factors of Indian materials to suit functional units provided in the EPiC database. Table 3 shows details of material-wise consumptions for each house under study and the aggregated case (CR-T). The table indicates that the study bears a more significant boundary by covering 18 materials.

Table 3. Material inventory for the study cases

S. No.	Materials		Functional unit (FU)	House-wise material inventory [FU]				
				CR-1	CR-2	CR-3	CR-4	CR-T
1	Steel bars		kg	9,900	10,500	2,500	8,000	30,900
2	Cement			48,250	60,000	22,000	55,000	185,250
3	Sand			1,098,352	923,400	203,490	70,1100	2,926,342
4	Brick			196,000	157,500	77,000	147,000	577,500
5	Coarse aggregates (gravel)			145,001	118,400	59,200	128,000	450,601
6	Aggregate (fine)			503,713	357,835	108,560	375,978	1,346,086
7	Ceramic tiles			5,316	10,680	4,440	9,944	30,380
8	Marble stone			12,858	10,975	5,488	11,250	40,571
9	Granite			653	16,330	380	10,881	28,244
10	SS railing			70	200	100	100	470
11	Iron grill			650	900	400	300	2,250
12	Glass	Float	m^2	75	14	23	11	123
		Security		0	102	0	88.3	190
13	Paint (interior) water-based			1,620	2,565	1,080	2,430	7,695
14	Paint (exterior)			460	473	270	405	1,608
15	Paint oil-based			340	608	243	513	1,704
16	PVC			74.3	0	32.5	0	107
17	Wood		m^3	9.2	6.9	2.7	5.7	25
18	Plywood			0	8.82	0.428	6.21	15

The EPiC database holds the monopoly and uniquely provides hybrid embodied coefficients for *EC* (GHG), *EE* and *EW* for maximum building materials. The details of hybrid embodied coefficients for *EC*, *EE*, and *EW*, as per the chronology and FU of materials in **Table 3**, are expressed in **Table 4**. The *EW*, *EE* and *EC* coefficients are herein notated as α, β, and λ, respectively. The coefficient α is expressed in L/FU, β in MJ/FU, and λ in $kgCO_2e$/FU, as in **Table 4**.

Table 4. Detail of hybrid embodied coefficients (source: EPiC database)

S. No.	Material		Functional unit (FU)	Material-wise hybrid embodied coefficients		
				α [L/FU]	β [MJ/FU]	λ [$kgCO_2e$/FU]
1	Steel bars		kg	37.1	38.8	2.9
2	Cement			7.8	11.8	1.3
3	Sand			1.8	0.34	0.024
4	Brick			1.8	3.5	0.32
5	Coarse aggregates (gravel)			1.9	0.48	0.036
6	Aggregate (fine)			1.9	0.48	0.036
7	Ceramic Tiles			15.2	18.9	1.3
8	Marble Stone			16.5	16.3	1.3
9	Granite			16.5	16.3	1.3
10	SS Railing			168	123	9.2
11	Iron grill			44.3	29.5	2.1
12	Glass	Float	m^2	335	296	21
		Security		785	775	56.9
13	Paint (interior) water-based			16.1	8.7	0.53
14	Paint (exterior)			14.7	9.3	0.47
15	Paint oil-based			14.7	9.3	0.47
16	PVC			670	574	26.7
17	Wood		m^3	58,411	41,597	2,269
18	Plywood			69,363	63,691	3,680

Impact assessment

The equations presented on the next page outline the total impacts for *EW*, *EE*, and *EC* for the disaggregated or aggregated houses, house-wise and material-wise. The calculated impacts of *EC*, *EE*, and *EW* on the study cases are represented in **Table 5**. The materials initially listed as 18 groups are rearranged here into 15 groups (combining the sub-groups under aggregates, paint, and glass) to simplify the impact revelations. **Table 5** also clarifies the total house-wise quantities of *EC*, *EE*, and *EW* in the specified units in the last row.

Table 5. Material and house-wise *EC* [$kgCO_2e$], *EE* [MJ], and *EW* [L] assessment details

	Impact assessment house-wise (disaggregated cases)											
	CR-1			CR-2			CR-3			CR-4		
Material	*EC*	*EE*	*EW*	*EC*	*EE*	*EW*	*EC*	*EE*	*EW*	*EC*	*EE*	*EW*
Steel	28,710	384,120	367,290	30,450	407,400	389,550	7,250	97,000	92,750	23,200	310,400	296,800
Cement	62,725	569,350	376,350	78,000	708,000	468,000	28,600	259,600	171,600	71,500	649,000	429,000
Sand	26,360	373,440	1,977,034	22,162	313,956	1,662,120	4,884	69,187	366,282	16,826	238,374	1,261,980
Brick	62,720	686,000	352,800	50,400	551,250	283,500	24,640	269,500	138,600	47,040	514,500	264,600
Aggregates	23,354	311,383	1,232,557	17,144	228,593	904,847	6,039	80,525	318,744	18,143	241,909	957,558
Ceramic tiles	6,911	100,472	80,803	13,884	201,852	162,336	5,772	83,916	67,488	12,927	187,942	151,149
Marble stone	16,715	209,585	212,157	14,268	178,893	181,088	7,134	89,454	90,552	14,625	183,375	185,625
Granite	849	10,644	10,775	21,229	266,179	269,445	494	6,194	6,270	14,145	177,360	179,537
SS railing	644	8,610	11,760	1,840	24,600	33,600	920	12,300	16,800	920	12,300	16,800
Iron grill	1,365	19,175	28,795	1,890	26,550	39,870	840	11,800	17,720	630	8,850	13,290
Glass	1,575	22,200	25,125	6,098	83,194	84,760	483	6,808	7,705	5,255	71,689	73,001
Paint	1,235	21,534	37,842	1,868	32,369	57,187	814	14,167	24,929	1,719	29,678	52,618
PVC	1,984	42,648	49,781	0	0	0	868	18,655	21,775	0	0	0
Wood	20,875	382,692	537,381	15,656	287,019	403,036	6,126	112,312	157,710	12,933	237,103	332,943
Plywood	0	0	0	32,458	561,755	611,782	1,575	27,260	29,687	22,853	395,521	430,744
Total	256,021	3,141,854	5,300,449	307,346	3,871,609	5,551,120	96,439	1,158,677	1,528,612	262,718	3,258,001	4,645,644

The equations for the total impacts of *EW*, *EE*, and *EC* are following:

$$EW = \sum_{j=1}^{18} (\alpha_j Q_j) \tag{1}$$

$$EE = \sum_{j=1}^{18} (\beta_j Q_j) \tag{2}$$

$$EC = \sum_{j=1}^{18} (\lambda_j Q_j) \tag{3}$$

where Q_j denotes the quantity of the *j*-th material represented in functional units (FU).

As an example for better understanding, eq. (2) is represented in expanded form as eq. (4):

$$EE = \beta_1 Q_1 + \beta_2 Q_2 + \cdots + \beta_{18} Q_{18} \tag{4}$$

RESULTS AND DISCUSSION

Various impacts assessed in previous sections are interpreted under different set-ups using comprehensive system boundary analysis as described below.

Comparatives of total consumptions in disaggregated cases

Table 3 outlines the *EC*, *EE*, and *EW* consumptions with the change in the covered construction area of all disaggregated cases. The covered construction areas of all the disaggregated cases are plotted on the X-axis, while the Y-axis shows the quantities per functional unit as specified. The callouts in **Figure 3** showcase the Y-axis entry corresponding to the respective construction area from the X-axis. **Figure 3** shows that CR-2 possesses uniformly the highest *EC*, *EE*, and *EW*. CR-3 evidence the lowest consumption for all three components. CR-2 has the largest covered area (391 m^2), and CR-3 has the smallest covered area (107 m^2) among all disaggregated cases. So, the trend of consumption above, as illustrated in **Figure 3**, highlights the following:

I) The positive relationship between the covered area of construction and the impact quantities in the specified units. Quite generic, an increase in area is bound to result in higher consumption. An author **[29]** has expressed concern over the increased *EE* by increasing dwellings' floor area, owing to minimal improvisation in EEC of materials.

Further, **Table 2** shows CR-2 is larger in covered construction areas by 11.55%, 73%, and 3% than CR-1, CR-3, and CR-4, respectively. Total *EW* for CR-2 is larger by 4.5%, 73%, and 16% than for CR-1, CR-3 and CR-4, respectively, as concluded from **Figure 3**. *EE* is higher by 19%, 70%, and 16% for CR-2 than *EE* values for CR-1, CR-3, and CR-4, respectively. In the case of *EC* (GHG), CR-2 exhibits higher values by 17%, 69%, and 15% than CR-1, CR-3, and CR-4, respectively.

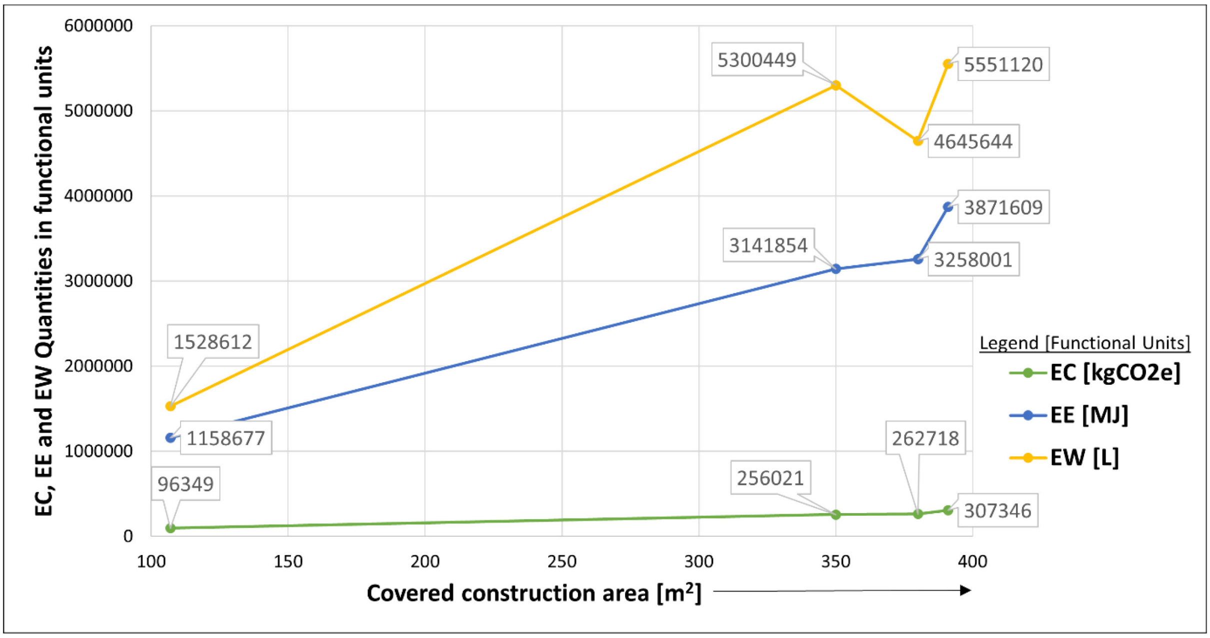

Figure 3. Illustration showing changes in *EC*, *EE* and *EW* consumptions as functions of covered construction area of all disaggregated cases

II) A single-storey non-RCC (CR-3) and a double-storey RCC frame construction house (CR-2) of significantly dissimilar areas exhibit a more pronounced and uniform positive relationship of *EC*, *EE*, or *EW* to the covered construction area. Notably, Indian scholars [71] advocated no correlation between *EE* and the mass of the building. CR-2 of significantly dissimilar areas exhibit a more pronounced and uniform positive relationship of *EC*, *EE*, or *EW* to the covered construction area. Notably, Indian scholars [71] advocated no correlation between *EE* and the mass of the building.

III) The percentage drop in the covered area of the houses does not correspond to the equal percentage variation in any of the three (*EC, EE, EW*) components. The covered areas for CR-2 and CR-4 are similar, yet *EC*, *EE* and *EW* consumptions for CR-2 outline considerably more than the rest of the cases (**Figure 3**). While *EE* and *EC* consumptions are marginally higher for CR-4 than CR-1, the 2nd highest *EW* consumption exists for CR-1 and is considerably higher than that of CR-4. The underlying basis is that CR-1 and CR-2 are RCC frame constructions while the others are composite. It outlines that:

IV) RCC constructions account for higher *EW* among conventional construction types, while the same may not hold equally well for *EE* and *EC*. The *EW* finding correlates with the study [12], while Indian studies [30-33] advocated the role of materials selection and construction techniques to reduce *EE*.

The need to cover an alternate boundary component arises to further the above findings, as scientific literature urges. Thus, house-wise and material-wise consumption per unit construction area of the houses is envisaged to comprehend the impacts better.

Disaggregated cases' consumptions per unit construction area

The respective disaggregated case impacts (**Table 5**) are illustrated in terms of the per unit covered construction area (**Table 2**) of each house in **Figure 4**. *EC* (GHG) consumption ranges from 691−901 $kgCO_2e/m^2$ across disaggregated cases, as per **Figure 4**. *EE* consumption range is 8,574−10,829 MJ/m^2. Different Indian conventional residential-based studies showcased the upper *EE* value of 10,510 MJ/m^2 [71], 9,360 MJ/m^2 [72] or 7,350 MJ/m^2 [31]. Australian studies reported a high *EE* of 13,000−14,400 MJ/m^2 [73-75]. The current study *EE* results are henceforth a strong indication that Indian constructions are doing all right in the *EE* domain owing to extensive research in previous decades. Further, Indian conventional constructions are better *EE*-conscious than their Australian counterparts. At the same time, current *EE* numbers might further recede if the EPiC (Australian) database is replaced with an Indian one.

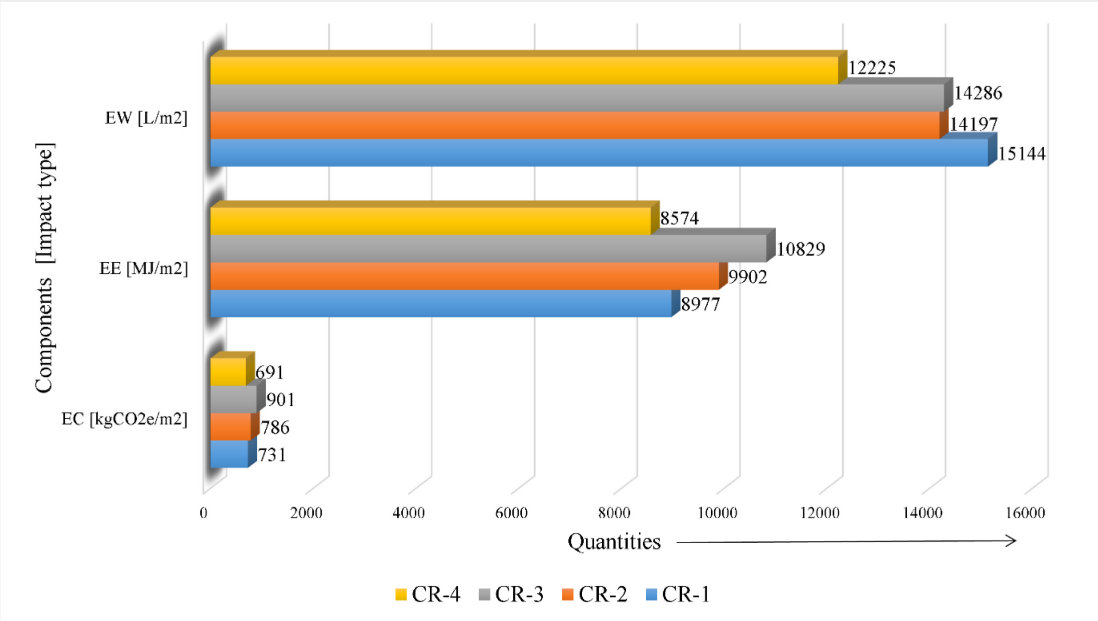

Figure 4. *EC*, *EE*, and *EW* impacts per unit area in disaggregated cases

Proponents [28, 76] argue that extensive human labour utilisation in Indian industry stands out in lesser values vis-à-vis electricity dominant production of other countries. An indication of high energy use in a developed country like Australia vis-à-vis developing one (India) cannot be ruled out.

EW consumption values show a range of 12,225−15,144 L/m^2 for the disaggregated cases in the pre-construction phase, as evident in Figure 4. A prominent office-based Chinese study [77] deduced *EW* = 10,430 L/m^2, while a prominent Iranian study [23] covering residential buildings found *EW* = 16,910 L/m^2. Previous stand-out Indian studies [10, 17] based on houses reveal a much higher *EW* range of 22,390−25,600 L/m^2, while a hotel-based Indian study [25] revealed an *EW* figure of 18,980 L/m^2 in the pre-construction phase. The EWC values used by Indian studies [17, 25] are debatable. However, *EW* quantifications could be overestimated more because the underlying focus is only on brick, steel, and cement. So, the lesser *EW* computation in the current study is attributed to EPiC database use and reflects continuous *EW* reforms in Australia, which is the initiator of *EW* research. It unravels that computation across contexts may vary. Nevertheless, high *EW* consumption in conventional Indian houses cannot be ruled out besides needing more consolidation studies. In crux, developed countries (Australia) are already water use conscious, but developing ones like India are still awaiting regulations to come out of UFW attitude.

Figure 4 shows the highest *EW* for CR-1 while CR-3 possesses the highest *EE* and *EC* computed per unit construction area basis. The descending pattern for *EE* and *EC* is similar, i.e. CR-3 > CR-2 > CR-1 > CR-4, while the *EW* consumption trend as per Figure 4 differs. House-wise *EW* consumptions reveal CR-1 > CR-3 > CR-2 > CR-4 trend in descending order. It leads to:

- A positive and uniform behaviour of *EE* and *EC* consumption in conventional houses concerning materials consumption correlates with studies [78, 79]. The trend of *EW* impacts across houses varies from that of *EE* or *EC* and primarily consolidates *EW*'s weak link to *EE* (or *EC*), as pointed out in studies [40, 80].

- Small single-storey constructions (CR-3) have the highest *EE* and *EC* consumption among the study cases. Relatively higher *EW* consumption for single-storey construction emerges irrespective of the construction technique or area of the houses. So, it is fitting to conclude that building components like the foundation are highly impacting. An Indian study targets only the foundation part to assess *EW* in hot-dry climates [81]. The Jammu house owners construct foundations to withstand two or three floors in future, irrespective of constructing a single floor initially. The high *EE* consumptive nature of foundations is also identified in studies [32, 82].

The results support at least double-storey construction in future conventional residences. Jammu is a potentially developing city, and like most Indian cities, high-rise solutions could have significance in checking *EW*, *EE*, and *EC*. As discussed, given the various pros and cons of vertical cities [66], the cost of a high-rise building apartment unit and the terrain of Jammu to support such constructions are also to be contemplated simultaneously. The interpretations for Figure 3 and Figure 4 need to be further analysed to arrive at consolidated conclusions. Learning from the previous Indian [10] or Australian [83] house-based studies, system boundary analysis predominantly considers material-wise consumptions per unit construction area. Only aggregated case-based interpretations are envisaged to avoid any undue complexity.

Aggregated case consumptions per unit construction area

Figure 5 clarifies the comparatives of aggregated (CR-T) material-wise *EC*, *EE* and *EC* impacts per unit construction area. The values are obtained by the ratio of the cumulative sum of consumptions for a particular material for all houses (Table 6) to the total construction area of all houses (1,228 m^2), as shown in Figure 5. All the impacts are shown in distinguished colours in text and illustration (bar and line) in Figure 5, as per specified units provided in the bottom half. Further, the negligible impacts stand ignored to be illustrated through text in Figure 5 for the illustration legibility.

Table 6. Material-wise *EC*, *EE*, and *EW* assessment for the aggregated case

Material	Impact assessment for the aggregated case (CR-T)		
	EC [kgCO_2e]	*EE* [MJ]	*EW* [L]
Steel bars	89,610	1,198,920	1,146,390
Cement	240,825	2,185,950	1,444,950
Sand	70,232	994,956	5,267,416
Brick	184,800	2,021,250	1,039,500
Aggregates	64,681	862,410	3,413,705
Ceramic tiles	39,494	574,182	461,776
Marble stone	52,742	661,307	669,422
Granite	36,717	460,377	466,026
SS railing	4,324	57,810	78,960
Iron grill	4,725	66,375	99,675
Glass	13,411	183,891	190,591
Paint	5,635	97,748	172,576
PVC	2,852	61,303	71,556
Wood	55,591	1,019,127	1,431,070
Plywood	56.885	984,535	1,072,213
Total	922,524	11,430,141	17,025,825

Figure 5 shows that cement (196.1 kgCO_2e/m^2) and brick (150.5 kgCO_2e/m^2) stand out from the rest of the materials for *EC* consumption. Similarly, cement (1,780.1 MJ/m^2) and brick (1,646.0 MJ/m^2) impact the *EE* criterion the most. However, sand (4,289.4 L/m^2) is the most impacting *EW* material, followed by aggregates (2,779.9 L/m^2).

The top *EC*-impacting materials are cement > brick > steel bars > sand > aggregates. The high *EE* and *EC* impact of brick, cement and steel are noted in Indian studies [47, 84]. *EE* impacts are pronounced for cement > brick > steel bars > wood > sand. Studies [82, 85-87] outline the high *EE* impacts of concrete and its constituents, while others emphasise significant high *EE* impacts for massive brick use in Indian conventional houses [30-33, 84]. Henceforth, proponents urge the adoption of AAC and concrete blocks as alternatives to massive brick use for combating *EE* [88].

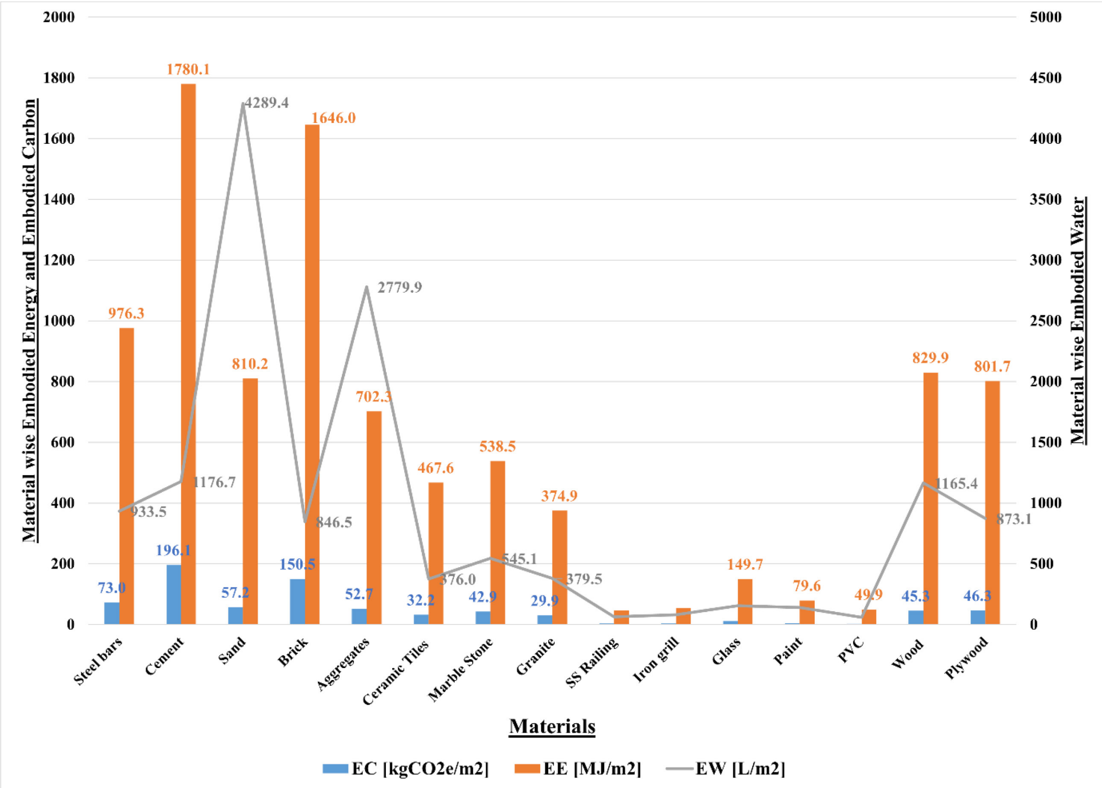

Figure 5. Material-wise *EC*, *EE*, and *EW* per unit area in aggregated case

Notably, prominent materials for *EW* impacts are sand > aggregates > cement > wood > steel bars. Figure 5 illustration interpolates to:

- An *EC*-conscious approach in selecting materials for conventional houses seems effective for *EE* conservation. The close association of *EC* (GHG) and *EE* has been consistently reported in the past, too [13, 89]. However, *EW* conservation requires broadening the *EC* or *EE*-conscious measures as sand and aggregates recede in priority for *EE* or *EC*. Outlined *EW*-specific attention for sand and aggregates is reported in a stand-out 2022 study [10] and studies [60, 90, 91].
- Brick impacts in *EW* fail to emerge in the top 5 materials, but it stands out for *EE* and *EC* impacts. Pertinently, before 2022, Indian studies [17, 25] target to cover *EW* aspects only for brick, steel, and cement (top *EE* consumptive ones). A broad system boundary coverage through a 2022 study [10] identified the role of sand, aggregates, and other materials for *EW* consumption in conventional Indian houses. The current study consolidates it further.
- Steel is not the prominent *EW* consumption material, contrary to previous scientific literature [17, 25], but consolidates the stand-out Indian studies of 2022 [10] and 2024 [50]. The marked Indian cities and current ones consider many materials beyond steel, cement, and brick. Moreover, the emphasis on steel-based resource consumption has been outlined for decades, greatly improving steel production. The *EW* debate's inception was owed to Australia in 2004, and the EPiC database of Australia reflects the much-improvised *EW* of steel production in Australia since 2004.
- The bottom line of the analysis arrives at a clear connection of *EE* and *EC*, but the *EW* aspect differs [14, 79].

Interrelationship assessment using regression technique

The relationship between the impacting components (*EC*, *EE*, and *EW*) is evident in the sections above, hinting at a strong and positive one between *EE*−*EC*. **Figure 6** and **Figure 7** clarify the extent of the mutual inter-relationship between the three components through statistical modelling using the regression technique (R^2 value). The material-wise *EC* consumptions per unit construction area in the aggregated case (like **Figure 5**) are plotted in the Y-axis, while corresponding *EW* and *EE* consumption values for all 15 materials are plotted in the X-axis, as per the specified units in **Figure 6**.

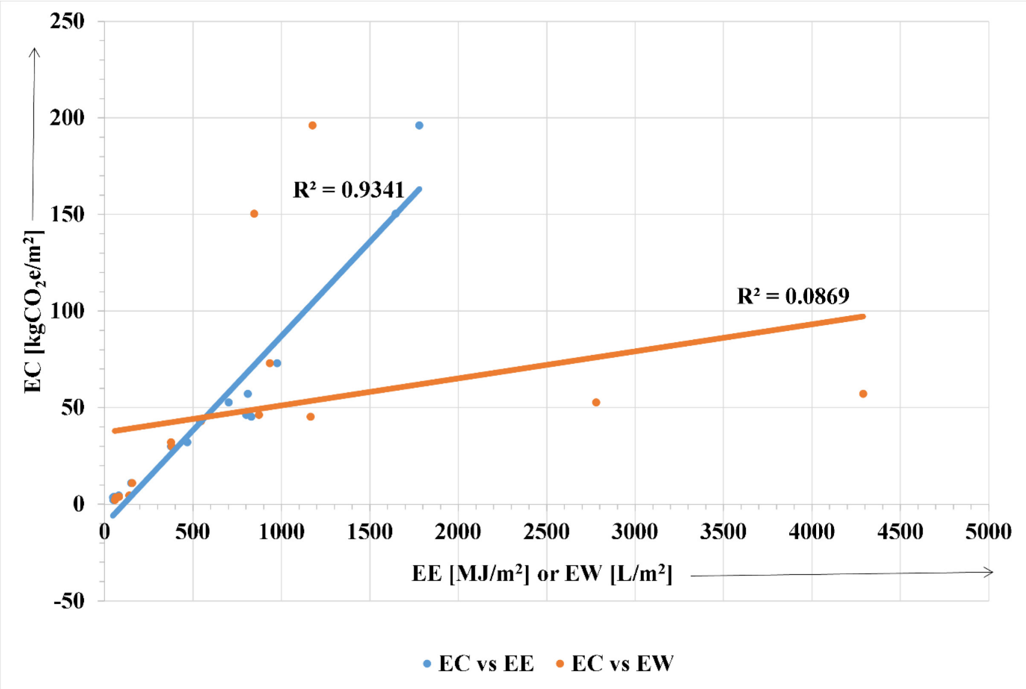

Figure 6. *EC* to *EE* and *EW* relationship graph using regression technique

The *EC* vs. *EW* relationship graph returns with an R^2 value of 0.0869, meaning 8.69% fitness of positive and linear relationship is evident, while *EC* vs. *EE* relationship fitness amounts to 93.4%. In other words, Figure 6 indicates a weak relationship between *EC* and *EW* and a strong and positive interrelation between *EC* and *EE*. Considering the material inventory and pre-construction LCA phase, the finding of a significantly weak *EC* (GHG) and *EW* relationship at the building level is nothing short of a breakthrough. In contrast, the solid and positive *EE*−*EC* relation strengthens the previous attempts **[13, 78, 79]**. It implies that *EE* measures over the preceding decades check the *EC* component. However, *EW* measures invite a different outlook, as the abovementioned sections prove. Figure 7 further crystallises the takeaways.

Figure 7 aims at the *EE* vs. *EW* relationship by plotting material-wise *EE* consumptions per unit construction area in the aggregated case (Y axis) and corresponding *EW* consumptions (X axis) for all 15 materials. The consumption values are plotted in consistent units and stand specified through the axis labels in **Figure 7**. It reveals the *EE*−*EW* relationship through an R^2 value of 0.1565, which means 15.65% strength of the positive and linear relationship. It translates as a weak *EE* to relationship considering the material consumption scenario of Indian conventional houses.

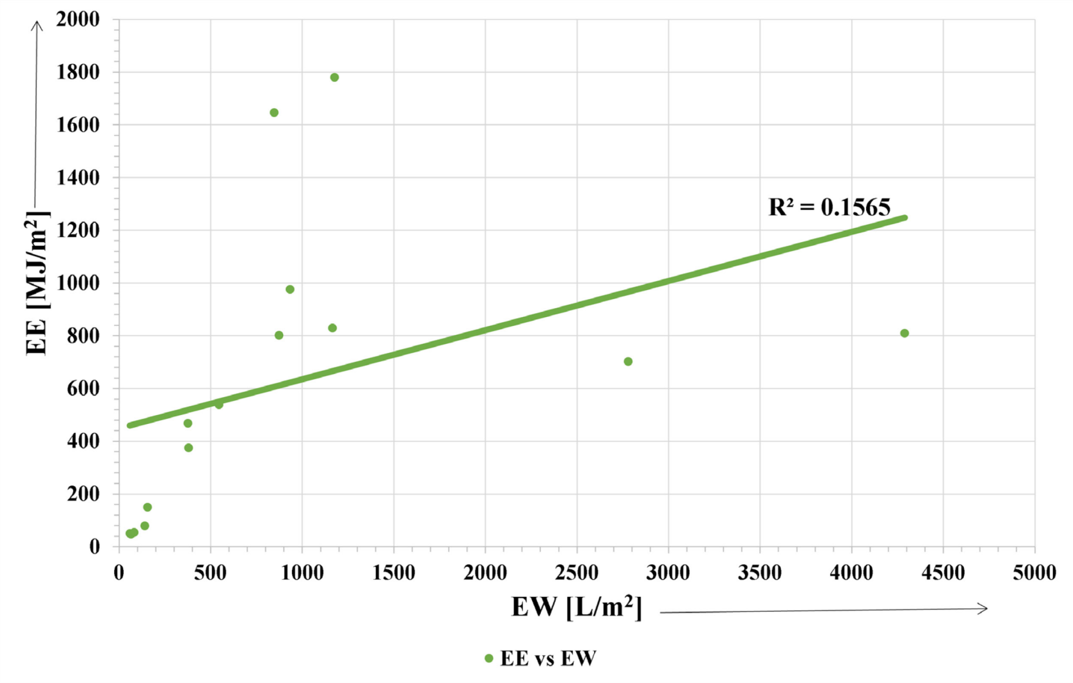

Figure 7. *EE−EW* relationship graph using regression technique

A weak *EE−EW* relationship is observed in a 2022 study [42] based on five institutional buildings and utilising the R^2 value approach. Another study [40] reflects the weak *EE−EW* relationship using the R^2 approach. While some studies [14, 42, 80] also find almost zero *EE−EW* relationship, interestingly, few studies [81, 92-94] hint at the probability of an *EE−EW* relationship to some extent. Nevertheless, various nexus studies, for example, a review study [4], find that 94% of the urban energy-water-carbon studies focus on the 'energy-water nexus' relationship instead of three components in one go at product or sector-level studies. So, a solid and positive *EE−EC* relationship and a weak *EE−EW* (and *EC−EW*) relationship seem to fit the global research scenario.

EPiC database tables show uniformity in positive or negative change in all three components (*EC*, *EE*, or *EW*) with change in unit material [61]. For example, if moving from material 1 to material 2 shows an EEC increase in EPiC, it would also increase EWC and ECC. So, a positive relationship interpretation reflects unit material consumption. However, the harmonious mix of material consumption patterns in conventional Indian houses demonstrates the strong *EE−EC* and extremely weak *EE−EW* or *EC−EW* relationships. So, quantity-wise material use pattern needs an interrogation to balance the three components in parallel.

It is observed that Jammu residences are discouraging wood use already. Reforms in the global steel and cement industry are also emerging consistently. The cessation of Jammu's informal brick industry is inevitable due to resource consumption, cost, and quality concerns. *EE* research over the last three decades is visible in the rise of various alternative materials to substitute the primarily consumptive ones like brick. Such alternative materials are expected to make a mark in conventional Indian houses. Various construction methods like rat-trap bonds exposed masonry in concrete or ceramic bricks check *EC*, *EE*, and *EW* simultaneously through decreased use of brick and abandoning the plasterwork (sand). Further, there are apparent advantages in on-site water use (reduced curing and material use), reduced construction period, and the cost involved.

A positive and robust interrelationship between *EE* and *EC* but differing *EW* behaviour calls for a broad materials template identifying the top simultaneous impacts. An *EW*-conscious approach in selecting materials for conventional houses may disregard the importance of steel, brick, or cement, which otherwise are prominent considering *EE* (or *EC*) impacts. The novel area of *EW* has outlined materials like sand and aggregates. Amid the high global water-related concerns, *EW*'s approach deserves an overriding preference. Considering the combined matrix of *EC*, *EE*, and *EW*, it is essential to consider a high-impacting material palette. If wood use continues to be discarded in the conventional houses and *EE* reforms (strongly correlated to *EC*) are consolidating continuously, the *EW* impacting materials approach to devising a broad materials template is fitting. A refined approach under the *EW* umbrella, but with specific attention to brick, cement and steel, would unleash a new approach towards building sustainability in the 21st century. So, taking a holistic preview and recalling the outcomes of **Figure 6** and **Figure 7** besides **Figure 5**, this study proposes to conserve *EC*, *EE*, and *EW* by attending the use of the following materials: sand > aggregates > cement > steel bars > brick > plywood.

The current study is indeed subjective to conventional Indian constructions of Jammu. Nevertheless, it opens valuable horizons to the knowledgeable audience. Thanks to the established *EE* research, localised *EE* databases are in place. The *EC* has its basis directly in *EE*, so its determination is near exactitude using localised databases. However, *EW* assessment is an infant and untouched domain, yet the databases are seldom noticed, barring the Australian one. Pertinently, the use of global databases is recommended by the proponents irrespective of the context; for example, the EPiC database is applied for American [95], Mediterranean [96, 97], and Indian [10, 50] context-based studies. The identification and trend of top impacting materials on *EW* and *EE* are the same despite different databases consultation [50]. So, it is worthwhile to avoid getting carried away with the quantitative assessment; the chronology of the impacting materials, building elements, or construction phases holds significance. Thus, the study's outcome in establishing a materials-wise chronology for the comparative $EC-EE-EW$ assessment is valuable. Sustainable built environments are thus better envisioned by holistically considering the combined matrix of *EC*, *EE*, and *EW* in conventional constructions.

By reflecting on the impact of material use based on a single parameter or all three parameters, architects and societal players must seek and contemplate improvisations to better introspect in the A+D phase of buildings. The Indian manufacturing industry is relatively informal and primarily dependent on human labour. So, if and when the Indian database emerges, it can reflect differential *EE*, *EC*, and *EW* quantifications. Therefore, as already discussed, different databases return different quantities; hence, databases used have a subjective role. Still, based on a global database, the study reflects reverse psychology. It could encourage the industry to transpire *EW* numbers honestly and consolidate the knowledge bank for different regions and countries. *EE* research also flourished in a similar pattern in previous decades. The consumption numbers and specifically accentuating the top impacting materials in this research are still clinical vis-à-vis scientific literature. EPiC database is Australian-based, and it was the first country to intervene in the *EW* matter in 2004. It reflects the unit material-wise consumption for all three parameters, so the controls and assumptions, if any, remain the same. Using global databases, especially the EPiC database, is logical for now. The latest and continuously improvising databases like EPiC are understood to provide clinical resource consumption values (both direct and indirect) by including comprehensive and complex production steps, such as extraction of ores, in the case of steel production. Nevertheless, manufacturing reforms are also becoming identical in the current globalised era, making our findings increasingly rigorous.

After the inception of *EW* studies in 2004, the Australian manufacturing industry improved in *EW* conservation measures. While unregulated, irresponsible, and higher water consumption in most other countries, including India, there are lags in reporting in scientific literature. Through its massiveness, the Indian construction industry is pivotal in resource consumption in other countries. When coupled with UFW's association with Indians, the water consumption scenario is enormously scary. The Indian construction sector already reflects much higher *EW* based on the current results. The quantifications go haywire when adding the 30% non-revenue water component attributed to only the leakages component in the country's water supply scenario. So, the study aptly urges global academia and research groups to adopt global databases to create awareness about current *EW* consumption and further contemplate conserving *EW*.

On the methodology front, it has sufficient scope to replicate across different global regions for both *EW* assessment and its nexus to *EE* (or *EC*). The I-O method is not logical, acknowledging the absence of economy-based data in the Indian context. I-O methods bring many sectors into calculations, further resulting in overestimation, while the unreliability of developing nations' economies is another challenge. Process-based methods almost invariably lag the comprehension to take all complex micro-level steps of a process, which results in underestimation. Using hybrid processes utilising accurate material inventories is fruitful, particularly in the scarce *EW* domain. The study considers only one process, i.e. material production phase (cradle-to-gate approach); multiple processes can be included in advanced *EW* studies in cradle-to-site or cradle-to-grave assessments. Since there are trade-offs between water and energy, developing a similar methodology, future studies can include further construction processes like on-site construction phase water use, electricity, and fuel consumption (indirect water) in on-site construction, material supply chain and workforce-related water and fuel consumptions. Knowing the various inventory from the site data and field investigations, *EW* assessment for a broader boundary condition and varied building typologies is inevitable.

Given the non-realisation of responsible water use behaviour without stringent policy reforms, user and facility-level water auditing is hard to find. Further, conventional houses are the ideal representation of Indian construction and seldom involve any attention to conservative resource use. Therefore, attending conventional typologies is more valid than conducting studies based on easy data availability. For now, hybrid and triangulation approaches for data collection as per the best of site records and availability (in consumption units or currency) should not be a barrier to conducting *EW* studies. Therefore, the current study should urge the researchers to follow suit and intervene in the dominant construction typologies in the respective regions.

The outcomes of the study are realistic and pragmatic. By developing the study outcomes, it is possible to unleash the effectiveness of the localised construction and architecture practices among the masses and administration. Realising more empirical studies are valuable in conserving resource consumption and having a checklist for dos and don'ts in the prevailing practices. Building bylaws and development controls can be redevised, considering materials, construction area, and number of floors vis-à-vis the plot size and economic status of the user. Auditing is the first step towards creating awareness. However, the current study is a lasting effort to encourage design, user, and policy interventions. The peer group must highlight the governing issues of current building construction practices and should seek ways to conserve resource efficiency, including *EW*. Indeed, it is time to test *EE*-conscious practices concerning *EW* consumption and the harmonious mix of A+D and other user-level approaches to wisely cater to all three parameters.

The current study, therefore, is much more than an auditing-only exercise. The research is novel to seek the interrelationship between the three components simultaneously. The current world is realising fast that water is indispensable to the future liveability of the planet, including any efforts towards SBE practice. The fact that *EE*- or *EC*-conscious solutions are not conserving *EW* is a realistic breakthrough to perceive future SBE. It unleashes a new horizon vis-à-vis the feeble existing research to consider even two components. A current study is a valid approach to seeking more contributions from academia and the material industry. The scope of the relationship equation between *EC*, *EE*, and *EW* is left to future studies with a larger sample. Various material and construction reforms need a broad outlook for consistent adaptation through technical platforms like sensitivity analysis, BIM applications and simulations. Techniques like AHP and TOPSIS can be helpful to draw conclusions involving experts and construction actors. Conventional constructions predominantly disobey the building regulations, too. So, the cost factor of the solutions is also worth intriguing as conventional construction clients have more orientation towards cost-cutting and efficiency. While studies can think of alternate solutions in constructions, our study has taken a more pragmatic approach of not deviating from the current practices. Instead, tweaking the current ones is more likely to get adopted in the Indian context. With *EE* research consolidated enough already while *EC* is strongly connected to it, the *EW* research invites profound contributions to seek a sustainable built environment in the 21st century and beyond.

CONCLUSION

The study is a novel attempt to seek *EC*, *EE* and *EW* assessments and their interrelationships in a single study. While the study consolidates the close association of *EE* and *EC*, it outlines the stand-out and differential behaviour of *EW* impacts stronger than the other two components for the conventional houses of Jammu in the pre-construction phase. A weak relationship unravels between *EW* to *EE* or *EW* to *EC*. The unprecedented study opts for a consistent database (EPiC) providing the hybrid embodied coefficients of building materials for all three components: *EC*, *EE*, and *EW*. The following findings stand out:

- There is a positive and strong correlation of $EE-EC$.
- *EE*'s conscious approach over the decades is controlling *EC*, too, but not the *EW* in building construction. *EW*'s conscious approach needs a varied canvas for construction techniques and building materials.
- Cement, brick, and steel are dominant *EE* and *EC* impacts. However, sand and aggregates are the top *EW*-impacting ones. Brick does not even make it to the top 5 *EW*-impacting ones.
- Indian conventional constructions seem considerate around *EE* already, while high on *EW* component vis-à-vis other prominent global works.
- To cut the three components simultaneously, building professionals need to consider material-wise attention in the order of sand > aggregates > cement > steel bars > brick > plywood.
- Global databases and material inventory are recommended for such studies across regions, primarily the infant *EW* domain.
- Steel is not the topmost *EW*-impacting material, contrary to the previous studies.
- Single-storey conventional houses are top *EE* and *EC* impacting while showing significantly high *EW*, too, hinting at the high foundation impacts on the three components. Conventional houses in Jammu should be at least double-storey.
- RCC constructions have a high *EW* impact, while the same does not hold for *EE* or *EC*.

Previous *EW* studies' approach to only considering top *EE*-impacting materials for identifying *EW* impact deserves significant improvisation. In the current study, recognising *EW* impacts for sand, aggregates, and plywood stands out. The study contributes to *EE* or *EC* research regarding assessments and relationships. It is a precious contribution to the scarce *EW* domain through various findings, while the first such attempt to outline the $EW-EC$ relationship. The comparative relationship of *EE*, *EW*, and *EC* helps architects, society, and policymakers to seek better sustainable solutions and defy the emphasis on a single aspect of *EE*. The results outline the suitability of previous approaches, whether the energy-conscious building is equally *EW*- or *EC*-efficient. The research is novel and unfolds interesting yet critical aspects of approaching conventional buildings' architectural design and construction.

The results call for more contributions to the study's outcomes to identify the material use and alternatives. Improvised LCA boundary conditions in future nexus studies are inevitable. Simulation studies and techniques like sensitivity analysis, TOPSIS, and AHP are envisaged for future attempts in this domain. The key to seeking sustainable built environments is to pay specific attention to *EW* research and associated impacts outlined in the study.

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NOMENCLATURE

EC	Embodied carbon	[$kgCO_2e$]
EE	Embodied energy	[MJ]
EW	Embodied water	[L]
Q	Quantity of the material	[FU]

Greek letters

α	Embodied water coefficient	[L/FU]
β	Embodied energy coefficient	[MJ/FU]
λ	Embodied carbon coefficient	[$kgCO_2e$/FU]

Subscript

j	Index of material or group of materials

Abbreviations

A+D	Architecture plus Design
AAC	Autoclaved Aerated Concrete
AHP	Analytic Hierarchy Process
BIM	Building Information Modeling
ECC	EC Coefficient
EEC	EE Coefficient
EREW	Energy Related EW
EWC	EW Coefficient
EPiC	Environmental Performance in Construction
FU	Functional Unit (kg, m^2, or m^3)
GHG	Greenhouse Gas
LC	Life Cycle
LCA	LC Assessment
OE	Operational Energy
OW	Operational Water
RCC	Reinforced Cement Concrete
SBE	Sustainable Built Environment
SDG	Sustainable Development Goals
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UFW	Unaccounted for Water use
VW	Virtual Water

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