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LEED-NC platinum-certified industrial manufacturing space projects in Bangladesh and their environmental assessment

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ABSTRACT

This study aimed to investigate the Leadership in Energy and Environmental Design for New Construction (LEED-NC) version 3 (v3) platinum-certified industrial manufacturing space projects in Bangladesh via a life-cycle assessment (LCA). A total of 27 LEED-NC v3 projects were sorted by the energy and atmosphere (EA) "optimize energy performance" credit (EAc1) achievement: 12 projects with the highest EAc1 achievement were collected in Group 1, and 12 projects with the lowest EAc1 achievement were collected in Group 2. Significance tests demonstrated that Group 1 and Group 2 differed based on different achievements in EA, as well as in their materials and resources (MR) credits: namely, EAc1, EAc2 "on-site renewable energy", and MRc1.1 "building reuse–maintain existing walls, floors, and roof". Regarding LCA, MRc1.1 was used in the production (P) stage, and EAc1 and EAc2 were used in the operational energy (OE) stage. The ReCiPe2016 endpoint results show that, in the P stage, the Group 2 strategy resulted in the least environmental damage ($p = 0.0030$), while in the OE stage, the Group 1 strategy resulted in the least environmental damage ($p = 0.0130$). However, the overall P + OE score showed the same environmental damage, as based on both certification strategies ($p = 0.4699$). The contribution and novelty of this study lie in its design, which makes it possible to compare at least two LEED certification strategies in the same country, and therefore to select the best alternative among the green building projects in a particular country.

1. Introduction

Table 1 demonstrates the acronyms and designations of the categories and credits for the green rating systems of Leadership in Energy and Environmental Design (LEED) for New Construction version 3 2009 and version 4 2013 (LEED-NC v3 and LEED-NC v4, respectively), as well as the terminology for life cycle assessment (LCA) used in this study.

1.1. Green building development in different countries

For the U.S. Green Building Council (USGBC), green buildings (GBs) are defined as "the planning, design, construction, and operations of buildings with several central, foremost considerations: energy use, water use, indoor environmental quality, material section and the building's effects on its site" [1]. One of the key methods for measuring the evaluations of GBs in the world is the creation of a green building rating system (GBRS). The first GBRS, BREEAM (Building Research Establishment Environmental Assessment Method) was launched in the United Kingdom in 1990. In 1998, the GBRS, LEED (Leadership in Energy and Environmental

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Design) system was launched in the USA. Zhang et al. [2] noted that, by 2019, there were already 49 green building systems worldwide. This may indicate the active growth of green development across the world. However, despite the significant progress of green building development in many countries, Zhang et al. [2] noted that “a common problem is the lack of a systematic social education scheme that can provide a clear understanding about the concept of GB to those who can incorporate it into a building life cycle”. Alternatively, Liu et al. [3] highlighted that while current green building encounters certain challenges, advancements in this field will yield a substantial reduction in environmental damage within the construction sector.

1.2. Progress in green building research

Among other GBRSs, LEED is one of the most commonly used GBRSs in the world [2]. The popularity of the LEED system is supported by the modification of version (v) of LEED from LEED v1 to LEED v4.1—through LEED v2, LEED v2.2, LEED v3, and LEED v4—and this was performed in order to increase the adaptability of the LEED system to different climatic conditions, cultural characteristics, and to the levels of building technologies that are found in different countries [4]. In this respect, LEED v3 introduced other pathways for East Asia, Europe, and South America, and a regional priority (RP) category was constructed that allows one to award four bonus points for paying attention to local regional priority environmental problems [5].

The LEED v3 system includes five main categories—sustainable sites (SS), water efficiency (WE), energy and atmosphere (EA), materials and resources (MR), and indoor environmental quality (EQ)—and two additional categories, innovation in design (ID) and RP. Each category includes one or more credits with a maximum number of possible points. According to the total sum of the achieved points, projects can be categorized as certified (40–49 points), silver (50–59 points), gold (60–79 points), or platinum (80+ points).

Based on the adaptability of the LEED methodology, different countries can select certification strategies that are appropriate to their climate, building technology, resource availability, and demographic and cultural features. Different strategies are used in the US and China for LEED-NC v3-certified projects: the US chose high achievement in EA, while China chose high achievement in SS and WE [5]. In Turkey, LEED-NC v3-certified projects must achieve high points in SS and WE [6]. In Vietnam, LEED-NC v3-certified projects are focused on high achievement in SS, WE, and EQ [7]. While it is clear that research on LEED certification strategies has reported different ways through which to obtain the same certification in different countries, the problem is that different strategies can result in different environmental consequences. This problem is acceptable since each country chooses its own certification strategy according to its own specific characteristics.

In 2020, two research papers examined the impact of moving from v3 to v4 in LEED-certified projects in two country pairs: China versus the USA [8], and Finland versus Spain [9]. Both of these studies noted that v4, rather than v3, in LEED-certified projects provides a greater adaptation to each country’s specific green building needs. In addition, in 2022, different space types in LEED-certified projects showed the different LEED certification strategies [10]. There are currently several studies that analyze the influence of space type on GB strategies. Thus, in order to fill this gap, the space type must be studied in terms of a LEED certification strategy.

Table 1
LEED-NC v3 and LCA expressions.

Abbreviation	LEED Category/Credit or LCA Expressions	LEED/LCA
IP	Integrative process	LEED v4 category
LT	Location and transportation	LEED v4 category
SS	Sustainable sites	LEED v3 and v4 category
WE	Water efficiency	LEED v3 and v4 category
EA	Energy and atmosphere	LEED v3 and v4 category
MR	Materials and resources	LEED v3 and v4 category
EQ	Indoor environmental quality	LEED v3 and v4 category
ID	Innovation in design	LEED v3 and v4 category
RP	Regional priority	LEED v3 and v4 category
SSc5.1	Site development—protect or restore habitat	LEED v3 credit
SSc6.1	Stormwater design—quantity control	LEED v3 credit
EAc1	Optimize energy performance	LEED v3 credit
EAc7	Optimize energy performance	LEED v4 credit
EAc2	On-site renewable energy	LEED v3 credit
EAc4	Enhanced refrigerant management	LEED v3 credit
EAc6	Green power	LEED v3 credit
MRc1.1	Building reuse—maintain existing walls, floors, and roof	LEED v3 credit
MRc7	Certified wood	LEED v3 credit
OE	Operational energy	LCA term
FU	Functional unit	LCA term
LCI	Life cycle inventory	LCA term
LCIA	Life cycle impact assessment	LCA
ReCiPe2016	LCIA method	LCA

1.3. LEED green rating system: a research gap

In the first step, when analyzing the certification performance of LEED-certified projects, the statistical analysis was carried out for one large group, which contained various LEED rating systems (e.g., new construction, core and shell, commercial interiors, etc.), and this was conducted without taking into account the space type of the LEED projects [11]. At the next stage, when analyzing LEED cross-certification performance, statistical analysis was used to compare two or more groups containing the same set of LEED-certified projects from different countries (for example, the USA, China, Brazil, etc.), and this was conducted without taking into account the space type of the LEED projects [12]. At the next stage, when analyzing the life-cycle assessment (LCA) of LEED certification strategies, statistical analysis was used to compare two groups within a single US state (California, USA) [13], as well as within a single city (Shanghai, China) [14], or within one borough (Manhattan, New York City) [15]. It should be noted that, for California, Shanghai, and Manhattan, the same rating system and the same space type were used. Thus, to obtain the right statistical inference and to avoid sacrificial pseudoreplication, it is necessary to compare groups with the same rating system and the same type of space at the city or even at the district level [16].

Thus, the approach described above is a promising avenue for exploring the different certification strategies in different countries. However, the LCA results of certification strategies highly depend on building type, certification level, country-specified building technology, and fuel sources [17].

1.4. LEED-certified industrial manufacturing projects

In this respect, the LCAs of the LEED-NC certification strategies of industrial manufacturing factories, such as those producing readymade garments (RMGs), is of special interest. This is because this type of building uses large amounts of water, energy, and chemicals for production and operation [18]. Currently, according to the USGBC and Green Building Information Gateway (GBIG) databases, the largest number of LEED-NC v3 and v4 gold- and platinum-certified industrial manufacturing projects are located in Bangladesh (115) [19,20]. RMG (industrial manufacturing) factories have multiple eco-friendly aspects such as optimized energy by using solar energy, efficient water consumption by harvesting rainwater, and improved workplace-related indoor environmental quality [18]. Platinum projects need to achieve the highest number of total points during the certification. Thus, these projects usually require additional effort to achieve high EAc1 “optimize energy performance” scores, where there is up to a maximum possible score of 19 points for this credit [21]. Thus, it can be speculated that the study design proposed by Ref. [15] could reveal different LEED platinum certification strategies for RMG manufacturers from an LCA perspective.

According to the literature, the LCAs of LEED-NC platinum-certified industrial manufacturing projects in Bangladesh have not yet been studied. Therefore, the goals of this study were as follows: (i) to investigate the certification strategies of LEED-NC v3 platinum-certified industrial manufacturing space projects, and (ii) to estimate the LCA of the revealed certification strategies in Bangladesh.

1.5. Contribution and novelty

This kind of sorting reveals two certification strategies: low and high achievement in EAc1. It is well known that achieving EAc1 has a strong impact on the global warming potential during the operation phase of a building’s life cycle. Thus, using this study design reveals which LEED credits significantly improve the environmental performance through which to achieve the same level of certification in LEED-certified projects. The LCAs of the two groups (i.e., low and high EAc1 achievement) of LEED-certified projects help to select the best alternative in green building projects.

2. Methods

2.1. Data collection and sorting

The author found and collected 27 LEED-NC v3 and 8 LEED-NC v4 platinum-certified industrial manufacturing space projects in Bangladesh in two databases: USGBC and GBIG [19,20]. The sorting procedure was carried out in accordance with the “optimize energy performance” credit in the v3 (EAc1) and v4 (EAc7) (EA category) metrics for LEED-NC projects.

2.1.1. LEED-NC v3

Two groups of LEED-NC v3 projects were created according to an EAc1 credit performance. Group 1 contained 12 projects with the highest EAc1 credit performances, while Group 2 contained 12 projects with the lowest EAc1 credit performances. The 12 projects in each group allowed for reliable statistical comparisons between the groups [22]. Statistical comparisons were aimed at identifying the differences in credit achievement between the groups in the following categories: SS, WE, MR, EQ, ID, and RP. As a result, different achievements in EAc1 led to different achievements in other LEED credits, and vice versa. This made it possible to identify the different strategies for LEED certification in groups 1 and 2. These strategies are reported in the Results Section.

2.1.2. LEED-NC v4

First, 8 LEED-NC v4 projects were divided into 2 groups: Group 1 contained 4 projects with the highest EAc7 credit performances, while Group 2 contained 4 projects with the lowest EAc7 credit performances. The 4 projects in each group did not allow for a reliable statistical comparison between the groups [22]. Therefore, the median and effect size were used to determine the trend in further studies.

2.2. Nonparametric statistical analysis

Nonparametric statistical analysis was used to assess the difference between the 2 independent groups. LEED data were presented using the median and 25th–75th percentiles. If either of the groups contained either ordinal or interval data with low variability, Cliff's δ effect size [23] and the exact Wilcoxon–Mann–Whitney (WMW) test [22] were used. If either of the groups contained binary data, the natural logarithm of the odds ratio ($ln\theta$) effect size [24] and Fisher's exact 2 × 2 test with Lancaster's mid-*p*-value [25] were used.

2.2.1. Effect size explanation

Cliff's δ ranged between −1 and +1, and lnθ ranged from $-\infty$ to $+\infty$. In both δ and lnθ, (+) indicates that Group 1 is larger than Group 2, whereas (−) indicates that Group 2 is larger than Group 1, and 0 indicates overlap or equality.

Table 2 shows the absolute effect size thresholds (negligible, small, medium, and large) for Cliff's $\boldsymbol{\delta}$ and $|\, \boldsymbol{ln\ \theta}\, |$.

2.2.2. p-Value explanation

Precise 2-tailed *p*-values were explained via a neo-Fisherian significance assessment [28].

2.3. Life cycle assessment

The LEED-NCv3 certification strategies in Group 1 (highest EAc1) and Group 2 (lowest EAc1) were evaluated according to the LCA methodology. These include the following: (1) defining the functional unit (FU) and system boundaries; (2) performing a life-cycle inventory (LCI) for the specified FU and system boundaries; (3) performing life-cycle impact assessments (LCIAs) of the LCI; and (4) interpreting the LCIA results [29]. Building-related LCAs include three main stages: production (P); operational energy (OE) for the building's heating, cooling, and lighting needs; and demolition (D).

2.3.1. Functional unit and system boundaries

The EAc1, EAc2 "on-site renewable energy", and MRc1.1 "building reuse—maintain existing walls, floors, and roof" credits were differently achieved in both groups as they followed from the statistical analysis of the LEED achievements of groups 1 and 2. Thus, the boundaries of the system were limited to the EAc1, EAc2, and MRc1.1 achievements in groups 1 and 2.

To convert the EAc1, EAc2, and MRc1.1 achievements into LCA measurable inputs, the requirement of each of these credits were analyzed. According to LEED-NCv3 [21], EAc1 involves decreasing the OE, whereby 1–19 points are awarded for a 2–48 % OE reduction, and where every 2 % OE reduction is worth 1 point; EAc2 prescribes the replacement of non-renewable OE such as coal, oil, or gas with renewable OEs such as solar, hydro, or wind, where 1–7 points are awarded for replacing 1–13 % of non-renewable OEs with renewable OEs, and where every 2 % of OE renewable fuel being used is worth 1 point; MRc1.1 requires the maintenance of existing structural components such as floors, walls, and roofs, where 1, 2, or 3 points are awarded for maintaining 55, 75, or 95 % of these components, respectively.

In the case of the LCAs, the appropriate FU for EAc1, EAc2, and MRc1.1 was 1 m^2 of the building floor. In particular, the OE requirements for EAc1 and EAc2 allow for them to be considered at the OE stage (i.e., OEs that have been in use for 50 years of the building's lifetime, $kWh/m^2 \bullet 50$ years), and the MRc1.1 requirement is to preserve existing structural components, such that it can be considered at the P and D stages (quantities of building materials, kg/m^2). However, Stage D was excluded from the assessment due to the minor environmental impact that occurred in comparison with the P and OE stages [30]. In this respect, Fig. 1 shows the examined life-cycle stages (P and OE) within the system boundary and the stage outside (D) the system boundary. Please note that a detailed list of the building materials and fuels with associated manufacturing processes included in them is presented in Chapter 3.3.2. Preliminary results were achieved by converting the credit achievement into LCI input data (Table 7).

2.3.2. Life-cycle inventory

The LCI was carried out using the eco-invent database on the SimaPro platform, which has an extensive collection of materials that were used in the construction sector [31]. To complete the LCI for the P and OE stages, first, information was collected from the literature about the dimensions and building technologies of the main building components (floors, roofs, walls, and windows), as well as the OE sources and usage that were relevant to a typical industrial manufacturing building in Bangladesh (such as a ready-made garment factory). Then, using this information and the relevant eco-invent database records, the LCI for the P and OE stages in the certification strategies of groups 1 and 2 was completed. Sections 3.3.1 and 3.3.2. present detailed explanations of the preliminary results for the MRc1.1, EAc1, and EAc2 achievements, and include the conversions of these into LCI input data.

Table 2
The absolute effect size thresholds.

Effect Size Estimation Procedure	Negligible	Small	Medium	Large	Reference
Absolute Cliff's δ | δ|	<0.147	0.147	0.33	0.474	[26]
Absolute natural log odds ratio $\|ln\ \theta\|$	<0.51	0.51	1.24	1.90	[27]

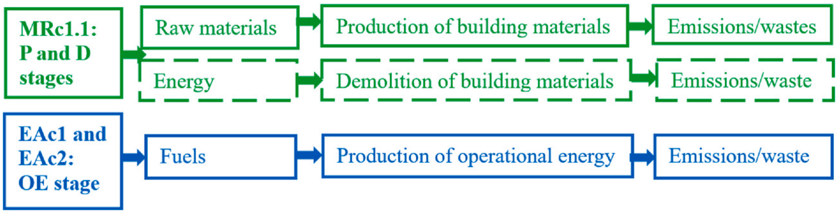

Fig. 1. LCAs of the MRc1.1: building reuse—maintain existing walls, floors, and roof; EAc1: optimize energy performance; and EAc2: on-site renewable energy credit achievements; Studied concrete system boundaries: plain line—included processes; dashed line—excluded processes.

2.3.3. Life-cycle impact assessment

ReCiPe2016 was used to convert the LCI of the certification strategies of groups 1 and 2 into LCIA [31]. This LCIA method was selected because it allows for the evaluation of LCA results at the midpoint (impact-based) and endpoint (damage-based) levels. Midpoint results are expressed in terms of the following environmental impacts: global warming potential, ionizing radiation, terrestrial ecotoxicity, human carcinogenic toxicity, water consumption, fossil fuels, and acidification impact. In total, 22 environmental impacts can be evaluated, and due to this large number, the interpretation of midpoint results can be difficult [32]. In this study, at the midpoint level, four of the most influential impacts, global warming potential, ionizing radiation, terrestrial ecotoxicity, and human carcinogenic toxicity, were evaluated.

In this respect, endpoint evaluation, which groups all of the impacts into 3 types of environmental damage—damage to human health, ecosystem quality, and resources—can be useful. It allows for the results to be interpreted easily. However, it also can add uncertainty to the results. This is because ReCiPe2016 uses average- and prospective-specified weighting sets for the damage, and it is through these that their relative importance is determined. It evaluates environmental damage over short, intermediate, and long time periods using individualist, hierarchist, and egalitarian perspectives, respectively. The endpoint single-score outcomes can be assessed using 6 methodological options: individualist/average (I/A), hierarchist/average (H/A), egalitarian/average (E/A), individualist/individualist (I/I), hierarchist/hierarchist (H/H), and egalitarian/egalitarian (E/E) [31]. In this study, at the endpoint level, all 6 methodological options were evaluated.

Fig. 2 shows the ReCiPe2016 endpoint single-score design structure [15]. The author of the current study used a two-stage nested analysis of variance test to evaluate the statistical difference between Group 1 and Group 2 [33].

3. Results

3.1. LEED-NC v3 certification strategies

Category level. Table 3 demonstrates that Group 1 outperformed Group 2 in the EA category, while Group 2 outperformed Group 1 in the SS and MR categories. Table 3 also shows that there is no difference between Group 1 and Group 2 for the rest of the categories (WE, EQ, ID, and RP ($0.3366 \le p \le 1.0000$)). As a result, the overall LEED scores show that Group 1 outperformed Group 2.

Credit level. The author of the current study only focused on the SS, EA, and MR categories at the credit level; this was performed because Group 1 and Group 2 differed in these categories. Table 4 shows only the LEED credits from these categories, and only those credits with different achievements between the two groups.

Table 4 shows that Group 1 outperformed Group 2 in EAc1; EAc2; and EAc4 “enhanced refrigerant management” credits, whereas Group 2 outperformed Group 1 in the remaining credits, i.e., SSc5.1 “site development—protect or restore habitat”; SSc6.1

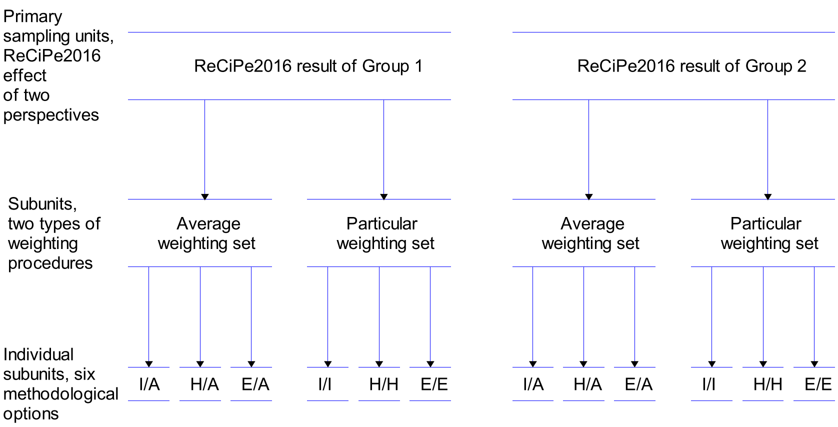

Fig. 2. Structure of the ReCipe2016 endpoint single-score method.

Table 3
LEED-NC v3 platinum-certified industrial manufacturing space projects at the category level in Bangladesh: Group 1 versus Group 2 ($n_1 = n_2 = 12$).

Category	Maximum points	Median, 25th–75th Percentiles		Cliff's δ	*p*-value
		Group 1	Group 2		
Sustainable sites (SS)	26	23.0 21.0–24.0	24.5 24.0–25.0	−0.56	0.0176
Water efficiency (WE)	10	10.0 9.0–10.0	10.0 8.5–10.0	0.08	0.8202
Energy and atmosphere (EA)	35	31.0 28.0–33.0	22.0 18.0–23.0	0.92	<0.0001
Materials and resources (MR)	14	6.0 6.0–6.0	7.0 6.0–9.0	−0.67	0.0024
Indoor environmental quality (EQ)	15	9.5 7.0–11.5	11.0 9.0–11.5	−0.24	0.3366
Innovation in design (ID)	6	6.0 6.0–6.0	6.0 6.0–6.0	−0.17	0.4782
Regional priority (RP)	4	4.0 4.0–4.0	4.0 4.0–4.0	0.00	1.0000
LEED total	110	87.0 84.5–90.0	82.5 81.0–85.0	0.65	0.0055

Categories in italics were used to estimate the difference between groups 1 and 2 at the credit level.

Table 4
LEED-NC v3 platinum-certified industrial manufacturing projects at the credit level in Bangladesh: Group 1 versus Group 2 ($n_1 = n_2 = 12$).

Credit	Maximum points	Median, 25th–75th Percentiles		ln θ/Cliff's δ	*p*-value
		Group 1	Group 2		
SSc5.1: Site development—protect or restore habitat[a]	1	0.0 0.0 1.0	1.0 1.0 1.0	−2.30	0.0111
SSc6.1: Stormwater design—quantity control[a]	1	1.0 0.0 1.0	1.0 1.0 1.0	−2.06	0.0490
EAc1: Optimize energy performance[b]	19	19.0 16.5–19.0	13.0 12.0–13.0	1.00	<0.0001
EAc2: On-site renewable energy[b]	7	7.0 4.0–7.0	3.0 0.5–4.5	0.53	0.0236
EAc4: Enhanced refrigerant management[a]	2	2.0 0.0–2.0	0.0 0.0–1.0	1.79	0.0341
EAc6: Green power[a]	2	0.0 0.0–2.0	2.0 1.0–2.0	−1.79	0.0341
MRc1.1: Building reuse—maintain existing walls, floors, and roof[b]	3	0.0 0.0–0.0	0.0 0.0–3.0	−0.42	0.0373
MRc7: Certified wood[a]	1	0.0 0.0–0.0	0.0 0.0–1.0	−2.06	0.0490

[a] Natural logarithm of the odds ratio (*lnθ*) and Fisher's exact test in a 2 × 2 table were used to estimate the difference between groups 1 and 2.
[b] Cliff's δ and the exact Wilcoxon–Mann–Whitney test were used to estimate the difference between groups 1 and 2. LEED credits in italics were used to evaluate the certification strategies using LCA.

"stormwater design—quantity control"; EAc6 "green power"; MRc1.1 and MRc7 "certified wood".

According to LEED-NCv3 [21], SSc5.1 requires that projects be established in previously developed areas; SSc6.1 involves implementing a stormwater management plan; EAc1 requires decreasing the OE; EAc2 prescribes replacing non-renewable OEs such as coal, oil, or gas with renewable OEs such as solar, hydro, or wind; EAc4 involves installing refrigerant, heating, ventilation, and air-conditioning (HVAC) equipment, such that emissions that contribute to ozone depletion and climate change impacts are minimized; EAc6 requires signing at least a 2-year renewable energy contract; MRc1.1 requires maintaining the existing structural components such as floors, walls, and roofs; and MRc7 requires using certified wood for flooring, doors, and finishes.

The above LEED credits are divided into two groups: credits that can and cannot be assessed by LCAs. The following credits, including reports, contracts, and site and interior plans, cannot be assessed by LCAs due to the lack of landscape and interior plans for LEED-certified projects: SSc5.1; SSc6.1; EAc4; EAc6; and MRc7. These credits are on a binary scale and therefore cannot be quantified for subsequent LCAs. The following credits can be assessed by LCAs, as they are independent of the landscape and interior plans for LEED-certified projects: EAc1; EAc2; and MRc1.1. These credits are expressed as interval data and can therefore be quantified for subsequent LCAs.

Table 5
LEED-NC v4 platinum-certified industrial manufacturing projects at the category level in Bangladesh: Group 1 versus Group 2 ($n_1 = n_2 = 4$).

Category	Maximum points	Median		Cliff's δ
		Group 1	Group 2	
Integrative process (IP)	1	1.0	1.0	−0.00
Location and transportation (LT)	16	13.5	12.0	0.19
Sustainable sites (SS)	10	9.5	10.0	−0.19
Water efficiency (WE)	11	10.0	11.0	−0.50
Energy and atmosphere (EA)	33	29.5	25.0	0.81
Material and resources (MR)	13	5.5	5.5	0.06
Indoor environmental quality (EQ)	16	7.0	8.5	−0.13
Innovation in design (ID)	6	6.0	6.0	−0.00
Regional priority (RP)	4	4.0	4.0	−0.00
LEED total	110	82.5	82.5	0.06

3.2. LEED-NC v4 certification strategies

Table 5 shows that Group 1 outperformed Group 2 in the EA category, and Group 2 outperformed Group 1 in the WE category. The effect size between groups for the remaining categories (IP, LT, SS, MR, EQ, ID, and RP) was negligible or small. As a result, the effect size between groups for the total LEED score was negligible ($\delta = 0.06$). Currently, having a small sample size limits the use of detailed statistical analysis and the LCAs for the LEED certification strategies in Group 1 and Group 2.

3.3. LCA of LEED-NCv3 certification strategies

3.3.1. Precursory outcomes: credit performance

Tables 6 and 7 show the credit achievements for EAc1; EAc2; and MRc1.1 for Group 1 and Group 2, respectively.

The LCAs for the EAc1, EAc2, and MRc1.1 credit achievements were performed for EMS Apparels Ltd. (Table 6) and SQ Birichina Ltd. (Table 7). These projects were selected because EMS Apparels Ltd. (Group 1) received 19 points (median) in EAc1, 7 points (maximum) in EAc2, and 0 points in MRc1.1 (minimum), and SQ Birichina Ltd. (Group 2) received 13 points in EAc1 (median), 0 points in EAc2 (minimum), and 3 points in MRc1.1 (maximum).

3.3.2. Preliminary results: converting credit achievement into LCI input data

According to LEED-NCv3 [21], MRc1.1 requires the maintenance of existing structural components such as floors, walls, and roofs, and awards 3 points for maintaining 95 % of these components. EAc1 involves decreasing the OE, and awards 19 points for a 48 % decrease and 13 points for a 36 % decrease in OE. EAc2 prescribes the replacement of non-renewable OEs (such as coal, oil, or gas) with renewable OEs (such as solar, hydro, or wind), and awards 7 points for replacing 13 % of non-renewable OEs with renewable OEs.

The MRc1.1, EAc1, and EAc2 credit performances for EMS Apparels Ltd. in Group 1 and SQ Birichina Ltd. in Group 2 were converted into LCI inputs using 1 m^2 of the building floor as the FU. As was noted in Section 2.3.1. Functional unit and system boundaries, the P stage includes MRc1.1, while the OE stage includes EAc1, and EAc2.

MRc1.1. According to Chowdhury et al. [34], the industrial manufacturing buildings used in Bangladesh for products such as ready-made garments are multistory (minimum three stories), and they have a rectangular floor plan with a wall-to-floor ratio of 0.8. They are built using brick walls that are 0.234 m thick, with windows occupying 20 % of the gross wall area; the floor height is 3.5 m; the window system includes aluminum frames of 0.005 m thick single-pane glass and 0.61 m deep external horizontal concrete shading devices; and the concrete floor and roof are 0.3 m thick. These building materials, and the dimensions of the building components, make it possible to take into account the quantities of materials that are used as input materials for the LCAs in the P stage with respect to the comparison between the two evaluated projects of EMS Apparels Ltd. And SQ Birichina Ltd.

EAc1 and EAc2. According to Paul et al. [35], for this type of building, the total OE related to fans, lights, air conditioners, and exhaust fans is 156 kWh/m^2•year. Using this base case and the OE percentages for EMS Apparels Ltd. in Group 1 (which had a 48 % decrease in non-renewable OEs for EAc1 and a 13 % use of renewable OEs for EAc2) and SQ Birichina Ltd. in Group 2 (which had a 36 % decrease in non-renewable OEs for EAc1 and a 0 % use of renewable OEs for EAc2), the resulting OE values for these two projects were evaluated.

Table 8 shows a summary of the quantities of materials from the P stage (which resulted from the requirements of MRc1.1) and energy from the OE stage (which resulted from the requirement of EAc1 and EAc2). These were obtained per the FU that were used as inputs for the LCI. Note that the material quantity data of the structural components (such as brick walls, concrete roofs, and floors) for EMS Apparels Ltd. In Group 1 were based on 100 % newly produced structural components, whereas for SQ Birichina Ltd. in Group 2, it was based on a 95 % maintenance of structural components. The material quantity data of the non-structural components such as wall paint and plaster, window glass and aluminum frame, roof bitumen sheets, and floor covering were the same for both certification strategies. During 50 years of the building's lifetime, the paint was replaced four times on both sides of the walls, the window glass and

Table 6
Platinum projects. Group 1: the points awarded for EAc1, EAc2, and MRc1.1 credit achievements.

Project			EAc1	EAc2	MRc1.1
No.	Name	Address	Achieved points		
1	AR Jeans Producer Ltd.	Palan Para, Khatgora, Zirabo, Savar, Dhaka, 1340	16	3	0
2	Cute Dress Industry Ltd.	Bathuli, Shaha, Beliswar, Dhamrai, Dhaka, 1800	16	7	0
3	Vintage Denim Studio Ltd.	Ishwardi Export Processing Zone, Pabna, 732	16	5	0
4	UHM Ltd.	Plot 240–243, 255, Adamjee Zone, Dhaka, 0000	17	7	0
5	EMS Apparels Ltd.	Vumihin Road, Gobindabari, Dhaka, 0000	19	7	0
6	Mithela Textile Industries Ltd.	Khanpara, Duptara, Araihazar, Dhaka, 1230	19	7	0
7	Pioneer Denim Ltd.	Shahpur Bazar, Madhabpur, Habiganj, 3330	19	0	0
8	Tosrifa Industry Ltd—Fabric Division	Holding 121/1, Block H, Ward 7, Gazipur, 1714	19	7	0
9	Fatullah Apparels	B-68/1, Wapda Road, Jalkuri, Narayanganj 1420	19	7	0
10	RBL Tower	225, Singbari Road, Tiler Gati, Gazipur, 0000	19	6	0
11	Designer Fashion Ltd.	Gohail bari, Shimulia, Savar, Dhaka, 1345	19	7	0
12	PN Composite Limited	Ambagh, Konabari, Gazipur, 1346	19	3	0

EAc1: optimize energy performance; EAc2: on-site renewable energy; and MRc1.1: building reuse—maintain existing walls, floors, and roof.

Table 7
Platinum projects. Group 2: points awarded for EAc1, EAc2, and MRc1.1 credit achievements.

Project			EAc1	EAc2	MRc1.1
No.	Name	Address	Achieved points		
1	JKL, Admin & Daycare Bldg.	Mawna, Sreepur, Gazipur, 1740	8	4	0
2	Jinnat Knitwears Ltd., Printing Bldg.	Mawna, Sreepur, Gazipur, 1740	11	5	0
3	Columbia Washing Plant Ltd.	Baniarchala, Bhabanipur, Bhawalgar, 1740	12	2	0
4	SSG Fan Factory	Vaberchar, Gajaria, Munshiganj, 1510	12	7	0
5	Kaniz Fashions Limited	Plot A/80–A/82, BSCIC, Gazipur, 1700	12	4	3
6	Jinnat Knitwears Ltd., RMG Bldg.	Mawna, Sreepur, Gazipur, 1740	13	4	0
7	SQ ColBlanc Limited	Jamirdia, Valuka, Mymensingh, 2240	13	0	2
8	Green Textile Limited Unit 3	Nijhury Baraid Bazar, Baluka, Mymensingh, 0000	13	7	0
9	The Civil Eng Ltd., Woven & Unit 2	Plot 8, 9, 159, 160, Bagh Bari, Dhaka, 1347	13	2	3
10	SQ Birichina Ltd.	Jamirdia, Valuka, Mymensingh, 2240	13	0	3
11	Genesis Fashions Ltd.	Kaada Nandun, Gazipur, 0000	14	1	0
12	Kenpark 2	Plot 69–85, Karnaphuli Zone, Chittagong, 4204	14	0	3

EAc1: optimize energy performance; EAc2: on-site renewable energy; MRc1.1: building reuse—maintain existing walls, floors, and roof.

Table 8
Platinum projects: LCI data inputs for Group 1 (EMS Apparels Ltd. as a representative project) and Group 2 (SQ Birichina Ltd as a representative project).

Component	Material/fuel input	Group 1	Group 2	Data Source (eco-invent database [31])
MRc1.1: Building reuse—maintain existing walls, floors, and roof				
Wall	Paint (kg)	2.24	2.24	Alkyd paint, without solvent/RER
	Lime mortar (kg)	14.4	14.4	Lime mortar, at plant/CH
	Bricks (kg)	285	14.3	Brick, at plant/RER
	Cement mortar (kg)	8	8	Cement mortar, at plant/CH
Window	Glass (kg)	4.2	4.2	Flat glass, uncoated, at plant/RER
	Aluminum frames (kg)	86.4	86.4	Aluminum extrusion profile/RER
	Concrete shading shelves (kg)	76	3.8	Concrete, normal, at plant/CH
Roof	Concrete (kg)	368	18.4	Concrete, normal, at plant/CH
	Bitumen sheets (kg)	19.2	19.2	Bitumen, at refinery/CH
Floor	Concrete (kg)	368	18.4	Concrete, normal, at plant/CH
	Ceramic tiles (kg)	40	40	Ceramic tile (GLO) market
EAc1: Optimize energy performance				
Natural gas (kWh/m^2•50 years)		3529	4992	Energy, natural gas/CH
EAc2: On-site renewable energy				
PV (kWh/m^2•50 years)		527	–	Energy, PV/CH

Note: According to the eco-invent database, paint production includes the transport of raw materials and production of paint; lime mortar and cement mortar includes raw material provision and mixing, and packing; brick includes the grinding, mixing, forming, cutting, drying, and firing of raw materials; glass includes the raw material provision, melting, forming, and cooling; aluminum includes the recycling of aluminum scrap and whole manufacturing processes to produce aluminum; concrete includes the whole manufacturing process to produce ready-mixed concrete; bitumen includes waste-water treatment and process emissions; ceramic tile includes raw material provision and the whole process regarding the production of ceramic tiles; natural gas usage includes the emissions and substances needed for operation; and PV usage includes waste heat emissions due to losses of electricity in the system [31].

aluminum frames were replaced twice, and roof bitumen sheets were replaced four times.

Thus, the LCI model was built according to the quantities of materials and energy (inputs) and eco-invent relevant data sources determined for the two evaluated projects (Table 8). As was noted in Chapter 2.3.3. Life-cycle impact assessment, global warming potential, ionizing radiation, terrestrial ecotoxicity, and human carcinogenic toxicity were evaluated at the midpoint level. Therefore, Table 9 presents the analyzed emissions to air for the LCI outputs that lead to global warming potential with a 0.5 % cut-off criterion (i.e., the only substances that contributed more than 0.5 % of the total environmental impact are presented). In this case, the cut-off flows were as follows: methane, fossil fuels; methane, tetrafluoro-, CFC-14; and methane, chlorodifluoro-, HCFC-22.

Table 10 presents the analyzed emissions to air, water, and soil for the LCI outputs that lead to ionizing radiation, terrestrial ecotoxicity, and human carcinogenic toxicity. These emissions were also used when applying the 0.5 % cut-off criterion. In the case of ionizing radiation, the cut-off flows were as follows: hydrogen-3, tritium; radon-222; iodine-129; and noble gases, radioactive, unspecified. In the case of terrestrial ecotoxicity, the cut-off flows were as follows: barium; chromium IV; acetic acid; beryllium; cobalt; and diflubenzuron. In the case of human carcinogenic toxicity, the cut-off flows were as follows: benzene; benzo(a)pyrene; lead; furan; formaldehyde; and cadmium.

3.3.3. Evaluating LCIA results

Midpoint level. Fig. 3 shows the ReCiPe2016 midpoint results of the group 1 and 2 certification strategies in terms of the following environmental impacts: global warming potential, ionizing radiation, terrestrial ecotoxicity, and human carcinogenic toxicity impacts.

Table 9
Global warming potential: the analyzed LCI data output emissions to air (impact indicators, 0.5 % cut-off) for Group 1 (EMS Apparels Ltd. as a representative project) and Group 2 (SQ Birichina Ltd as a representative project) [31].

Material/energy	Emissions to air (kg CO_2-eq)			
	Carbon dioxide, fossil	Carbon dioxide, land transformation	Methane	Methane, fossil
Group 1				
Paint	8.18	3.38	0.0000008	0.738
Lime mortar	8.45	0.00005	–	0.278
Bricks	65.6	0.00076	–	2.89
Cement mortar	1.49	0.00002	–	0.0465
Glass	3.97	0.00005	–	0.187
Aluminum frames	–	191	12.3	–
Concrete	84.6	0.00031	–	2.53
Bitumen sheets	8.26	0.00019	–	4.46
Ceramic tiles	41	0.0121	0.00002	5.58
Electricity: natural gas	1960	0.00484	–	176
Electricity: PV	0.63	0.00004	–	0.0606
Group 2				
Paint	8.18	3.38	0.0000008	0.738
Lime mortar	8.45	0.00005	–	0.278
Bricks	3.29	0.00004	–	0.145
Cement mortar	1.49	0.00002	–	0.0465
Glass	3.97	0.00005	–	0.187
Aluminum frames	–	191	12.3	–
Concrete	4.34	0.00002	–	0.13
Bitumen sheets	8.26	0.00019	–	4.46
Ceramic tiles	41	0.0121	0.00002	5.58
Electricity: natural gas	3000	0.00742	–	270

Table 10
Ionizing radiation, terrestrial ecotoxicity, and human carcinogenic toxicity: the analyzed LCI data output emissions to air, water, and soil (impact indicators, 0.5 % cut-off) for Group 1 (EMS Apparels Ltd. as a representative project) and Group 2 (SQ Birichina Ltd as a representative project) [31].

Impact (impact indicator)	Emissions to air, water, and soil
Ionizing radiation (kBq Co-60 eq)	Carbon-14; Cesium-134; Cesium-137; Cobalt-60; Radon-222
Terrestrial ecotoxicity (kg 1,4-DCB)	Cadmium; Copper; Lead; Mercury; Nickel; Selenium; Silver; Tin; Vanadium; Zinc
Human carcinogenic toxicity (kg 1,4-DCB)	Chromium VI; Dioxin, 2, 3, 7, 8 Tetrachlorodibenzo-p-; Formaldehyde; Nickel; PAH (polycyclic aromatic hydrocarbons)

The results of the four environmental impacts were not the same.

The analysis of global warming potential and human carcinogenic toxicity showed that the OE stage (EAc1 and EAc2) resulted in more significant impacts than the P stage (MRc1.1). This is due to high natural gas emissions such as carbon dioxide (CO_2) and sulfur dioxide (SO_2), which have a large influence on these impacts [36]. As a result, the certification strategy of Group 1 (lowest OE) resulted in lower global warming potential and human carcinogenic toxicity than that of Group 2.

However, when considering ionizing radiation and terrestrial ecotoxicity, the P stage (MRc1.1) resulted in more significant impacts than the OE stage (EAc1 and EAc2). Consequently, the certification strategy of Group 2 (highest percentage of maintained structural components) resulted in lower levels of ionizing radiation and terrestrial ecotoxicity than that of Group 1.

Such conflicting results regarding the preference for one or another certification strategy need to be reconsidered for a wider range of environmental impacts. This can be achieved by analyzing the endpoint damage-based results of ReCiPe2016.

End-point level. Fig. 4 shows the endpoint results of the 6 methodological options of ReCiPe2016 for the P stage, OE stage, and OE + P stages. In terms of the P stage, the Group 2 strategy (highest percentage of maintained structural components) showed less environmental damage than that of the Group 1 strategy ($p = 0.0030$).

In contrast, in terms of the OE stage, the Group 1 strategy (lowest OE) showed less environmental damage than that of the Group 2 strategy ($p = 0.0130$). However, in terms of LCAs (OE + P), both strategies showed similar environmental damage ($p = 0.4699$). Thus, the endpoint results confirm the previous intermediate results of the four impacts in terms of a wider range of environmental impacts, which—when combined—represent the environmental damage of the six considered methodological options in ReCiPe2016.

4. Discussion

The literature contains a detailed analysis of the interaction between LCAs and LEED. In 2002, Scheuer and Keolin [37] uncovered several inconsistencies within the LEED system. LCAs of single-point LEED credits yielded varying outcomes. In 2007, a notable disparity emerged between the achievements under the LEED framework and the results of LCAs [38]. In particular, credits with low

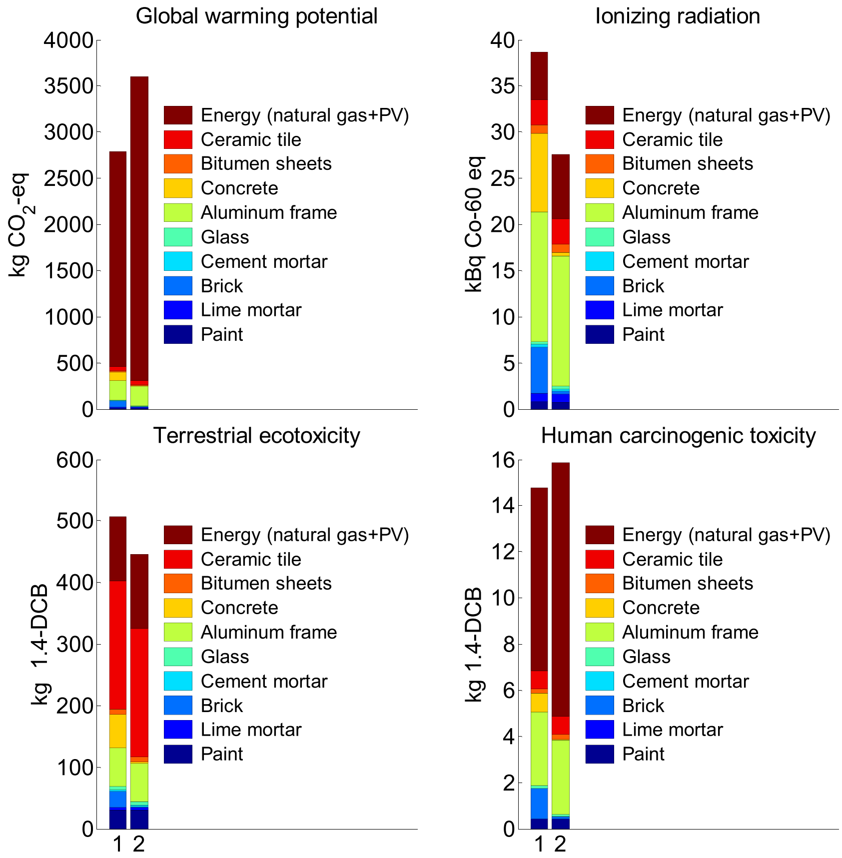

Fig. 3. ReCiPe2016 midpoint results of group 1 (EMS Apparels Ltd. as a representative project) and 2 (SQ Birichina Ltd as a representative project) certification strategies.

scores were linked to elevated LCA results, whereas credits with high scores resulted in diminished LCA outcomes [38]. By 2014, Alshamrani et al. [39] proposed the integration of LCA as an additional category within LEED. In 2016, De Wolf et al. [40] demonstrated that LEED does not focus on mitigating embodied impacts (materials and resources category).

In 2017, Al-Ghamdi and Bilek [41] concluded that, for the evaluation of operational energy in accordance with green standards, it is imperative to take into account the Life Cycle Assessment of locally-sourced energy. In 2018, Lessard et al. [42] noted that the elevated scores in the EAc1 credit of green standards could be attributed to the utilization of coal and natural gas for operational energy in buildings. However, advancements in renewable energy production are expected to diminish the significance of EAc1 within overall LEED values [42]. In 2019, Greer et al. [43] demonstrated that the outcomes of LCAs for the same LEED indicators were contingent on the source of local energy. In 2020, Ismaeel and Ali [44] conducted an LCA of the two MR credits (building reuse and construction waste management) toward a rehabilitation of the LEED-C&S (core and shell) gold project. They demonstrated the most sustainable scenarios in terms of demolishing/reusing and waste management practices for building components.

In 2023, Pushkar [14,15] evaluated the LCAs of the certification strategies, and showed that LEED-CI (Commercial Interior) v4 gold-certified office-space projects, with respect to the strategy of decreased damage from the OE stage (EA category), were more environmentally preferable than the strategy of decreased damage from the P stage (MR category). In contrast, in the current study, the results of LEED-NC v3 platinum-certified industrial manufacturing space projects show that both strategies, i.e., decreased damage from the OE stage (EA category) and decreased damage from the P stage (MR category), would lead to the same environmental outcome. This is due to the relatively small difference in the OE stage and the large difference in the P stage in the certification strategies of groups 1 and 2, as shown in Fig. 3.

5. Implications

The main implication of the study results is that high achievement in the EAc1 "optimize energy performance" credit from the LEED system significantly reduces the global warming potential in the building life cycle. This happens since the operational energy of the building, as part of the life cycle of the building, is mainly provided by fossil (non-renewable) energy sources (coal and gas). However, it was previously shown that when replacing non-renewable energy with renewable (photovoltaic) energy, the share of operational energy in the life cycle of building decreases, while the share of production energy increases, and—as a result—the priority of green

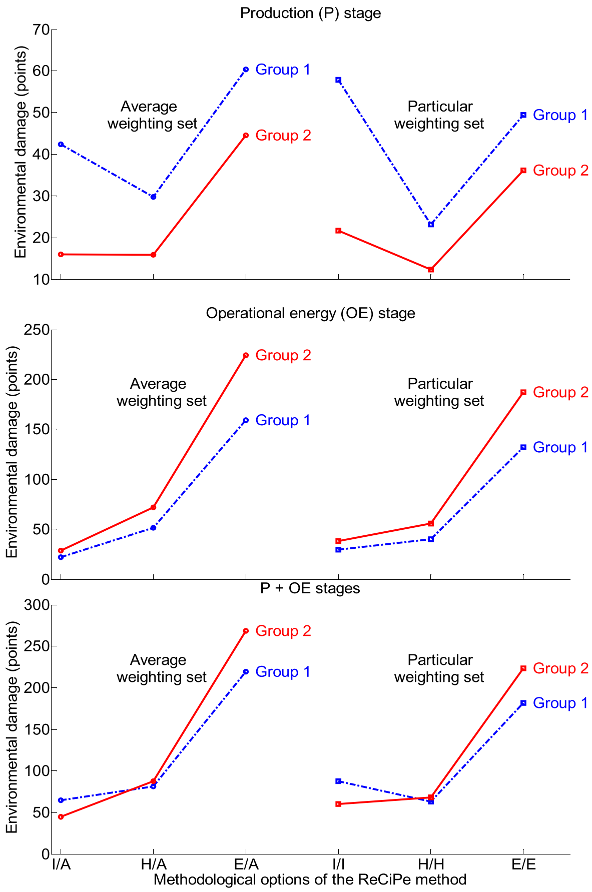

Fig. 4. ReCiPe2016 endpoint results of the certification strategies of groups 1 (EMS Apparels Ltd. as a representative project) and 2 (SQ Birichina Ltd as a representative project).

building materials increases [45].

6. Conclusions

This study evaluated the LEED-NC v3 platinum-certified projects and their LCAs for industrial manufacturing spaces in Bangladesh. The author of the current study studied two groups with different certification strategies for the LEED projects. In the EA category, Group 1 was associated with high achievement and Group 2 with low achievement.

Under LEED v3, at the same (platinum) level of certification, the LEED projects with high achievement in the EA category, when compared to those with low achievement, indicated greener buildings. With a low achievement in the EA category, the increased achievement in the SS and MR categories only partially compensated for the difference between the two LEED strategies.

In the next step, to retest the hypothesis that high achievement in the EA category leads to greener buildings, the author used the LCA method. The credits responsible for the differences between the two groups that could be used in the LCA were from the EA and MR categories, particularly EAc1: optimize energy performance); EAc2: on-site renewable energy); and MRc1.1: building reuse—maintain existing walls, floors, and roof. In the LCA method, MEc1.1 was used in the production (P) stage, and EAc1 and EAc2 were used in the operational energy (OE) stage.

The ReCiPe2016 midpoint results show that the highest MRc1.1 scores (P stage) of the representative LEED project of Group 2 resulted in the lowest ionizing radiation and terrestrial ecotoxicity impacts, whereas the highest EAc1 and EAc2 scores (OE stage) of the representative LEED project of Group 1 resulted in the lowest global warming potential and human carcinogenic toxicity impacts.

These results were confirmed in the evaluation of the ReCiPe2016 endpoint. The ReCiPe2016 endpoint showed that, in the P stage, the Group 2 strategy resulted in the least environmental damage, and, in the OE stage, the Group 1 strategy resulted in the least environmental damage. However, the overall P + OE score showed the same environmental damage from both certification strategies.

It can be concluded that, in the case of LEED-NC v3 platinum-certified projects for industrial manufacturing in Bangladesh, the two certification strategies of high EAc1 and EAc2 achievement, as well as low EAc1 and EAc2 achievement (with increased MR1.1 achievement) are ecologically the same.

The contribution and novelty of this study lies in its design, which—with the help of the EAc1 credit achievement—allows for a comparison of at least two LEED certification strategies in the same country.

This study has at least two methodological limitations: an insufficient sample size for statistical measurements and issues with LEED-certified projects (samples) and selection. In the LEED v3 projects, the small sample size (i.e., $n_1 = n_2 = 12$) revealed no significant difference between groups when the effect sizes were small or medium. In the LEED v4 projects, a small sample size (i.e., $n_1 = n_2 = 4$) could lead to a false statistical conclusion that there is no significant difference between groups (i.e., a significance test cannot reject a null hypothesis that is, in fact, false). The issues regarding samples and selection were based on the fact that both the USGBC and GBIG databases do not contain individual drawing plans for each LEED-certified project. As a result, it is not possible to evaluate the sustainable site category through a life-cycle assessment.

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Data availability statement

The data associated with this study is available at the USGBC Projects Site (available online at https://www.usgbc.org/projects) and the GBIG Green Building Data site (available online at http://www.gbig.org).

Ethics statement

This study did not require ethics committee review and/or approval because it did not involve human subjects or animals.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Svetlana Pushkar: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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