Status, constraints, and recommendations of green building certification for the expansion of green buildings in South Korea

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Abstract

Many countries have green building certification systems to rate a green building. South Korea has also launched its green building certification, known as the Green Standard for Energy and Environmental Design (G-SEED), to promote sustainable development. In this review, we focused on the certification status, regional distribution, types of certified buildings, and technical content of G-SEED. Additionally, we analyzed green building technologies applied to 48 sample buildings certified in 2020. Several proposals were formulated to promote the adoption of green buildings. All large cities and provinces in Korea have G-SEED-certified buildings, indicating that green building awareness is increasing. However, the number of green buildings remains less than the overall building stock. The government should revise the certification criteria and implement measures to disseminate green building technologies. Our findings will promote the development of green buildings and contribute to the sustainable development of the construction industry.

Keywords

Green building certification, Green buildings, Greenhouse gas reduction, Applicable technology, G-SEED[1]

[1] List of abbreviation: GHG: greenhouse gas; LEED: Leadership in Energy and Environment Design; BREEAM: Building Research Establishment's Environmental Assessment Method; CASBEE: Comprehensive Assessment System for Building Environmental Efficiency; G-SEED: Green Standard for Energy and Environmental Design; MOLIT: Ministry of Land, Infrastructure and Transport; MOE: Ministry of Environment; EPD: environmental product declaration; EPI: energy performance index; BECC: Building Energy Conservation Code; BEER: Building Energy Efficiency Rating; PM: particulate matter; TAB: testing, adjusting, and balancing; WWR: window-to-wall ratio; LCA: life cycle assessment; W/m^2: watts per square meter; m^2: square meter; $\mu g/m^3$: microgram per cubic meter.

1. Introduction

Green buildings are defined as structures that enhance sustainability and environmental performance throughout their life cycle [1]. Green buildings have been rapidly constructed on a large scale worldwide. Green building certification has played a pivotal role in promoting the adoption of green buildings [1,2,3]. Consequently, green building certification has become a significant policy tool for reducing building energy consumption and greenhouse gas (GHG) emissions [4]. Since the late 1990s, countries worldwide have developed their own green building certification systems to evaluate green buildings. Prominent examples include the Leadership in Energy and Environmental Design (LEED) in the United States, the Building Research Establishment's Environmental Assessment Method (BREEAM) in the UK, Green Star in Austria, Deutsche Gesellschaft fur Nachhaltiges Bauen in Germany, the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan, the Green Building Label in China, and Green Mark in Singapore [2,3]. South Korea has also introduced its green building certification system, known as the Green Standard for Energy and Environmental Design (G-SEED) [5,6,7].

In Korea, the green building certification system was first introduced for apartments in 2002. Subsequently, with the enactment of Korea's "Green Buildings Construction Support Act" in 2012, which came into force in 2013, G-SEED was expanded to cover all types of buildings [8]. The Korean government aims to achieve its GHG reduction targets through the widespread adoption of green buildings as outlined in its master plan for green buildings [9,10]. G-SEED evaluates green buildings or the eco-friendliness of buildings, aiming to create a comfortable indoor environment while reducing energy and resource consumption throughout the entire construction process. It also addresses pollutant emissions and environmental impacts [11]. This green building certification has existed in Korea for two decades. The 20th anniversary of G-SEED was celebrated at the "2022 Green Building Festival" organized by MOLIT, where the ministry announced plans for a comprehensive revision of the G-SEED certification criteria [12]. Furthermore, the 2022 annual report [13] underscored the need to improve G-SEED to prepare for the next 20 years.

Over the years, several studies on green buildings have been conducted in Korea. In some of these studies, G-SEED was compared with internationally implemented certification systems, such as LEED [14,7] and BREEAM [15]. Other studies have examined the acquisition of G-SEED certification and its evaluation results [16,17];

[18,19,20]. Additionally, there have been studies focused on improving G-SEED's assessment categories and detailed certification items [21,22,23,24,25,26,27]. However, an overview of Korea's green building certification is lacking, and no technical assessments related to G-SEED have been conducted. Therefore, to address this knowledge gap, this study aimed to analyze the situation of G-SEED-certified buildings in South Korea and the limitations of G-SEED. This study analyzed the technical characteristics of G-SEED-certified buildings. Based on this review and analysis, several proposals to promote the development and dissemination of green buildings, as well as possible revisions to the G-SEED certification system, are presented here.

The original contributions of this study are:

1) This study provides detailed information about South Korea's independent green building certification system, G-SEED, which is not well known in other contemporary studies. No study has attempted to address the technical characteristics of G-SEED certification and the status of certified buildings for 20 years. Therefore, this study provides a comprehensive assessment of green buildings and green building rating systems.

2) By analyzing the current status of G-SEED-certified buildings, this study revealed the weaknesses of the green building certification system. To address these weaknesses, this study provided valuable suggestions for revising G-SEED. These proposals would provide meaningful insights to stakeholders or decision-makers operating green building certification systems in other countries.

3) The results of the analysis of the application of green building technologies in actual certification projects allow readers of this paper to understand the technical level of green building. It also provides architects, building engineers, and building owners with information on how green buildings can be implemented.

Therefore, this study contributes to the improvement and development of the green building certification that realizes and promote green buildings. Additionally, this study facilitates communication on global sustainable construction and provide a deeper understanding of green building construction and certification.

2. South Korea's green building certification system, G-SEED

2.1 Operation and certificate of G-SEED

In Korea, green buildings or eco-friendly buildings are distinguished from conventional buildings through the G-SEED certification. MOLIT and the Ministry of Environment (MOE) are responsible for the operation and management of G-SEED. Under their authority, a unified evaluation standard for assessing the environmental performance of buildings and awarding green building certification was introduced in Korea. The Korean government laid the foundation for designating the National Green Building Center to promote the widespread adoption of green buildings. The National Green Building Center serves as the administrative body for G-SEED and performs various support functions, including revising G-SEED's certification assessment criteria, managing evaluation agencies, operating the certification management system, and promoting G-SEED [13]. Accredited evaluation agencies designated by the Korean government assess and certify target buildings in accordance with G-SEED's certification criteria. As of 2023, there are nine evaluation agencies nationwide responsible for G-SEED evaluations. Building owners are eligible to apply for G-SEED certification. The evaluation and certification process primarily includes the certification application, evaluation, judgment, and certificate issuance stages, as illustrated in Fig. 1.

The evaluation agencies issue the applicant a certificate, as shown in Fig. 2, according to the certification process. The certification results are uploaded along with a copy of the certificate and recorded in the G-SEED certification management system [28]. The building owner shall provide the issued certificate to the local authorities if necessary and place a plaque displaying the certificate grade, along with the G-SEED logo, at the entrance of the certified building (Fig. 3).

The G-SEED certification process for green buildings is divided into two stages: pre-certification and main certification. In the first stage, the contents of the planning documents from the design stage prior to building construction are evaluated. The main certification process is carried out for completed building projects. The main certification process involves evaluating and issuance of certifications based on design documents and on-site inspections carried out after the construction of the building. In the G-SEED system, buildings are classified into two main groups: residential and non-residential. Residential buildings include detached houses, conventional houses, and apartments. Non-residential buildings include offices, educational facilities, residential accommodations, retail spaces, and other types.

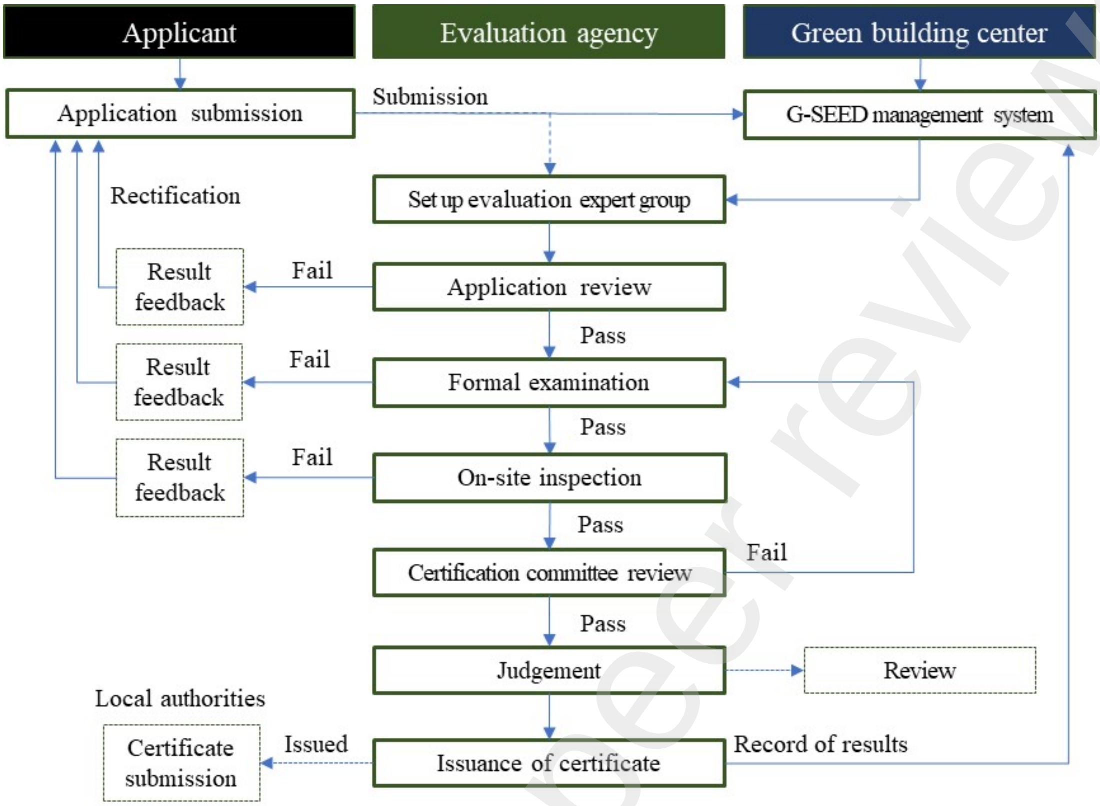


Fig. 1 Evaluation and certification process for G-SEED.

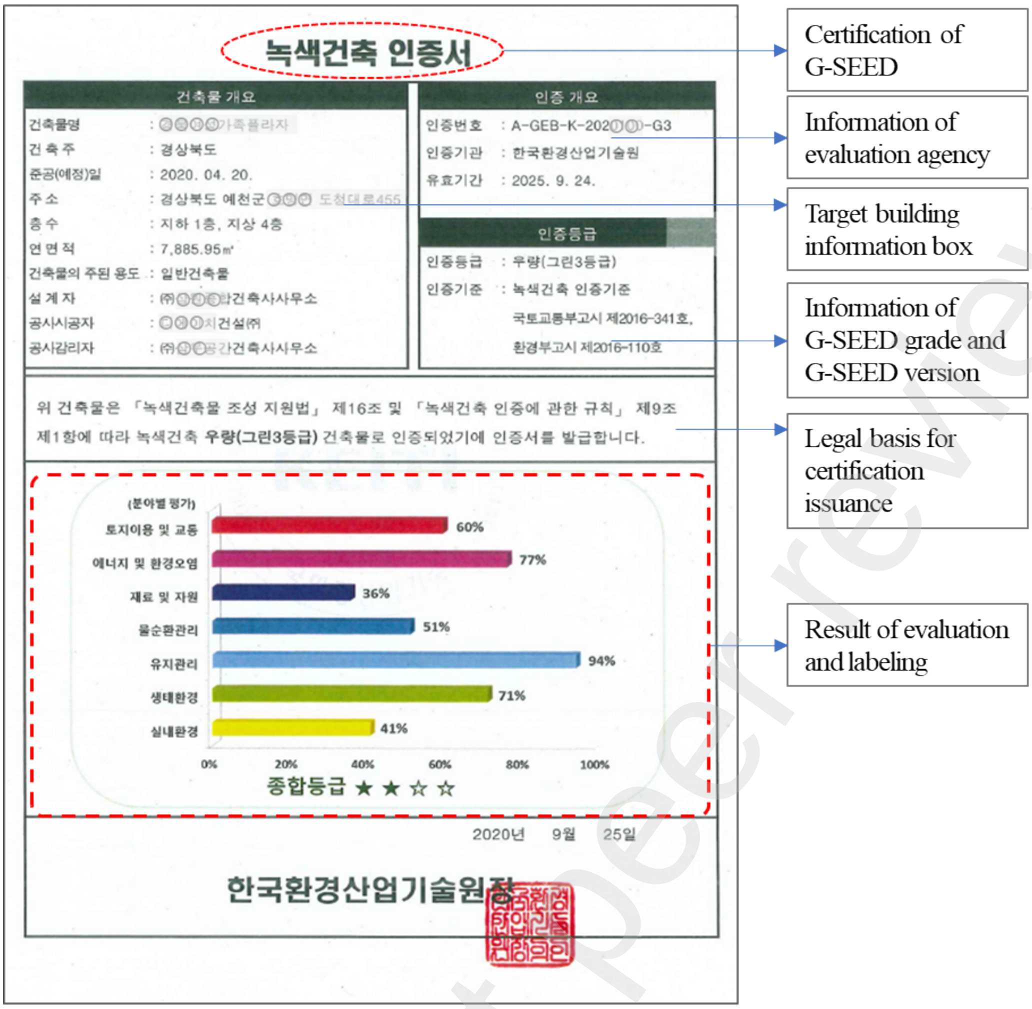


Fig. 2 Example of green building certificate by G-SEED

Fig. 3 Example of a plaque displaying G-SEED

2.3 Green building rating tool of G-SEED

G-SEED has seven field categories: “land use and transportation,” "energy and pollution," "materials and resources," "water management," "maintenance," "ecological environment," and "indoor environment quality". Each field category includes detailed certification items designed to evaluate the environmental performance of a building. The evaluation criteria, methods, and scores for these detailed certification items are outlined in the Standards for Green Building Certification [11], a governing regulation in South Korea. Detailed certification items and their corresponding points for each field category as of 2023 are presented in Table 1.

G-SEED encompasses 40 detailed certification items for residential buildings and 38 items for non-residential buildings, categorized into seven specific fields. Among these, 28 cases (68%) involve a single certification item with corresponding certification criteria. The level of each certification criterion is classified into four grades, and the score for the certification item is awarded differently depending on the grade. The other certification items incorporate two or more certification criteria, and the score depends on the number of certification criteria met. Notably, G-SEED and BREEAM share similarities in terms of certification items, certification criteria, and scoring methods [15].

G-SEED certification includes four grades, each marked with green stars to indicate the certification grade. The highest grade, Green 1, is denoted by four stars (★★★★). Green 2 is represented by three stars (★★★), Green 3 by two stars (★★), and Green 4 by one star (★) (Fig. 3). The G-SEED grade is determined based on the total score, which combines the final scores from seven field categories. For residential buildings, Green 1 (outstanding level) is awarded for scores of 74 points or higher, Green 2 (excellent level) for 66 – 73 points, Green 3 (very good level) for 58 – 65 points, and Green 4 (good level) for 50 – 57 points. In the case of non-residential buildings, Green 1 (outstanding level) is granted for a score of 80 points or more, Green 2 (excellent level) for 70 – 79 points, Green 3 (very good level) for 60 – 69 points, and Green 4 (good level) for 50 – 59 points.

Table 1. Certification items for the field categories included in the G-SEED 2016 version

Field category	Certification items	Points (score)	
		RB	NRB
Land use and transportation	Ecological value of existing land site	2	2
	Too much underground development is discouraged.	3	3
	Minimization of earthwork cutting	2	2
	Measures to impede the right to sunlight	2	2
	Pedestrian network in building complex	2	n/a
	Accessibility of public transportation	2	2
	Appropriateness of road and parking lot for bicycle	2	2
	Proximity to amenities	1	n/a
Energy and pollution	Energy performance	12	12
	TAB & commissioning	n/a	2
	Energy monitoring and supporting device	2	2
	Lighting energy saving	n/a	4
	Use of renewable energy	3	3
	Low-carbon energy source technology	1	1
	Prohibition of the use of specific materials to protect the ozone layer	2	3
	Plan for solar radiation control to reduce energy use for cooling	n/a	2
Materials and Resources	Use of EPD	4	4
	Use of low-carbon materials	2	2
	Use of recycled materials	2	2
	Use of hazardous substance reduction materials	2	2
	Ratio of applied green building materials	4	4
	Installation of storage facility for recyclable resources	1	1
Water management	Rainwater management	5	5
	Use of rainwater and groundwater runoff	4	4
	Use of water-saving equipment	3	3
	Water usage monitoring	2	2
Maintenance	Environmental management plan for the construction site	2	2
	Providing operation and management documents	2	2
	Providing user manuals	2	n/a
	Providing information on G-SEED certification	3	3
Ecological environment	Artificial green network	2	n/a
	Green area ratio of natural ground	4	4
	Ecological area ratio	10	6
	Making biotope	4	4
Indoor quality environment	Low-emission products of indoor air pollutants	6	3
	Natural ventilation performance	2	2
	Ventilation performance in household unit	2	n/a
	Design of air vents	n/a	2
	Installation of automatic temperature control device	1	2
	Measures for comfortable indoor environmental control system	n/a	2
	Sound insulation performance of lightweight impact	2	n/a
	Sound insulation performance of heavyweight impact	2	n/a
	Sound insulation performance of boundary walls between households	2	n/a
	Indoor and outdoor noise from traffic	2	2
	Noise of water supply and drainage in toilet	2	n/a

Creating an exclusive resting space in the building	n/a	1

TAB, testing, adjusting, and balancing; RB, residential building; NRB, non-residential building

3. G-SEED certification situation

3.1 G-SEED certification by year and certificate grade

G-SEED certification has been implemented for 20 years, with the number of construction projects receiving G-SEED certification significantly increasing each year. Preliminary certification was first provided to apartment designs in 2002, and G-SEED was first awarded in 2004 to three completed buildings. Since the certification of office buildings began in 2003, all buildings that received certification in 2004 were apartments. In 2010, a total of 278 buildings received the certification, followed by 510 buildings in 2015, 1,036 buildings in 2020, and 853 buildings in 2022. By 2022, a total of 12 buildings that underwent green remodeling received certifications [29]. The cumulative number of G-SEED-certified buildings reached 8,200 by 2022. Table 2 shows the number of certified buildings per year. Fig. 4 shows the number of certified buildings according to certificate grade per year.

All projects certified up to 2010 achieved Green 2 and Green 1 grades, with no instances of Green 3 and Green 4 grades. Subsequently, the number of certified buildings fell between 2010 and 2013. This decline can be attributed to the renaming of the certification to G-SEED and its major overhaul. Afterward, the numbers continued to rise. The number of certified buildings decreased in 2021 and 2022 as construction projects were delayed or suspended due to the impact of the COVID-19 pandemic.

The number of G-SEED buildings certified with the Green 1 grade was 365 (4.5%), followed by 2,676 (32.6%) for the Green 2 grade, 1,057 (12.9%) for the Green 3 grade, and 4,102 (50.0%) for the Green 4 grade (Fig. 5). The number of buildings certified with the Green 2 grade was greater than those certified with the Green 3 grade because the Korean government and local authorities mandated a Green 2 grade or higher for public buildings.

Table 2. Number of annual G-SEED certified buildings according to G-SEED grade

G-SEED grade	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Green 1 (★★★★)	1	2	2	6	11	10	9	12	19	29	43	39	31	35	24	28	26	25	13
Green 2 (★★★)	2	1	6	30	142	241	269	202	95	103	113	131	166	190	202	191	186	200	206
Green 3 (★★)									32	50	58	98	83	107	122	143	118	140	106
Green 4 (★)								4	33	59	137	242	287	416	505	610	706	575	528
Total	3	3	8	36	153	251	278	218	179	241	351	510	567	748	853	972	1036	940	853

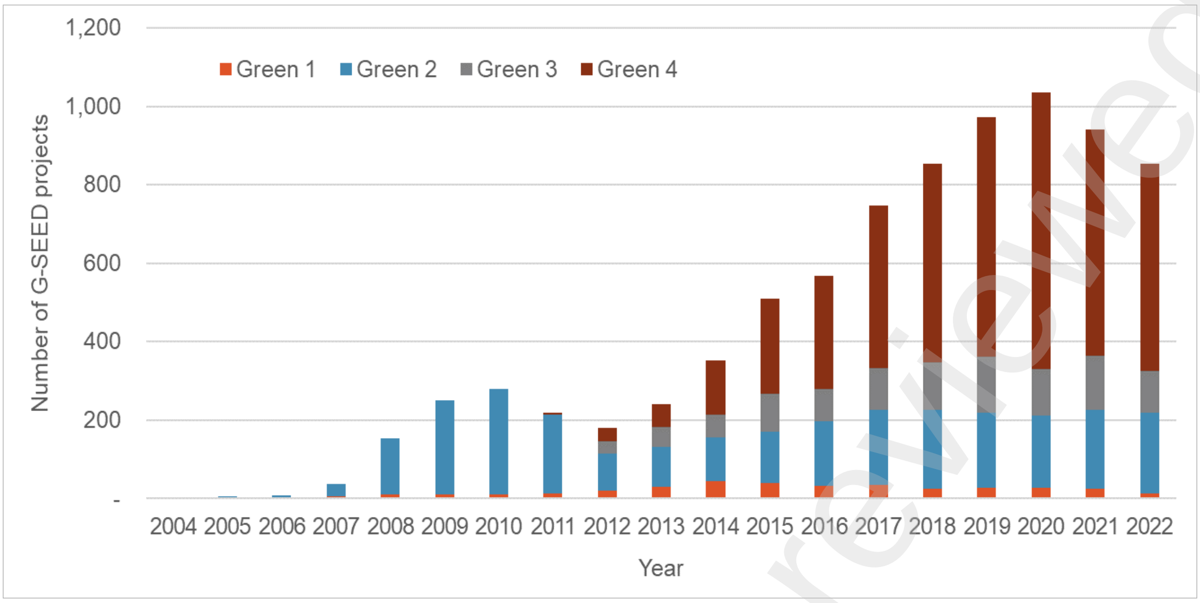


Fig. 4 Annual number of certified buildings according to G-SEED grade.

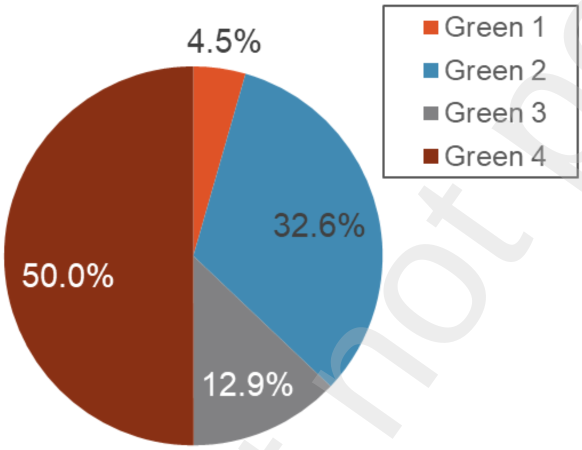


Fig. 5 G-SEED grade distribution among certified buildings

3.2 G-SEED certification by region

Building Energy Saving Design Standards [30] differ according to three regions based on Korea's climate zones. Fig. 6 shows the number of G-SEED-certified buildings categorized by region. The yearly fluctuations in these data are similar to the trends observed in Fig. 4. Notably, the total number of G-SEED-certified buildings in Korea is 8,199. The central region, home to approximately 60.2% of Korea's population, had the highest number of certified buildings (6,400 (78.1%)). The total number of certified buildings was 1,712 (20.9%) in the southern region and 87 in Jeju Island. In 2022, the Vietnam-Korea Institute of Science and Technology building, a new construction in Vietnam, received a Green 2 (Excellent) grade. This building is considered the first overseas building to receive G-SEED certification. The building that achieved G-SEED certification in Vietnam was excluded from Fig. 6 and Fig. 7 because it is located abroad and was evaluated using separate G-SEED certification criteria for Vietnam.

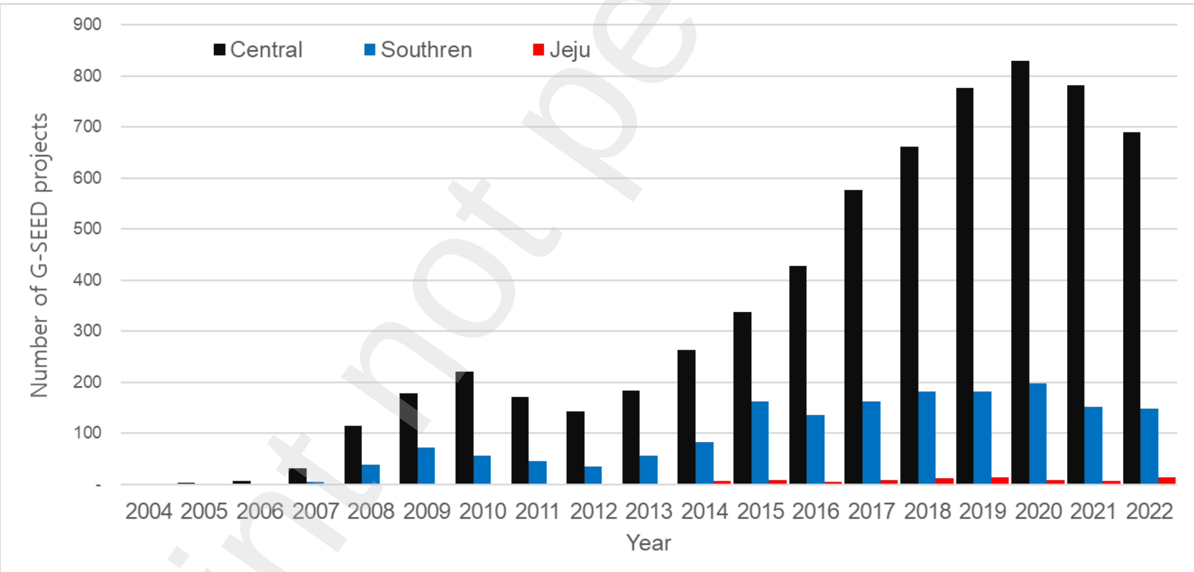


Fig. 6 Number of annual certified buildings according to province in South Korea

As shown in Fig. 7, G-SEED-certified buildings are distributed across all cities and provinces in Korea. Jeju Island has the lowest number (87) of certified buildings. Conversely, Seoul has the highest number (2,711) of G-SEED-certified buildings. It is noteworthy that the first certified apartment buildings were built in Seoul in 2004. Incheon has the second largest number (424) of certified buildings. Among local governments, Gyeonggi-do stands out with 2,098 certified buildings. On average, other local governments report 239 certified buildings each. Comparing the number of certified buildings, major cities account for 4,343 buildings, while local governments have 3,856 buildings, making the former approximately 6% larger. The number of green buildings constructed in the central region, covering Seoul and Gyeonggi-do, is 4,809, representing approximately 58.6% of all G-SEED-certified buildings. Sejong, a newly founded city in 2012, began constructing certified buildings the same year and has recently introduced green buildings; it now has the third largest number (282) of green buildings among cities. These observations indicate that G-SEED has been spread to all regions of Korea, and awareness regarding green buildings has increased.

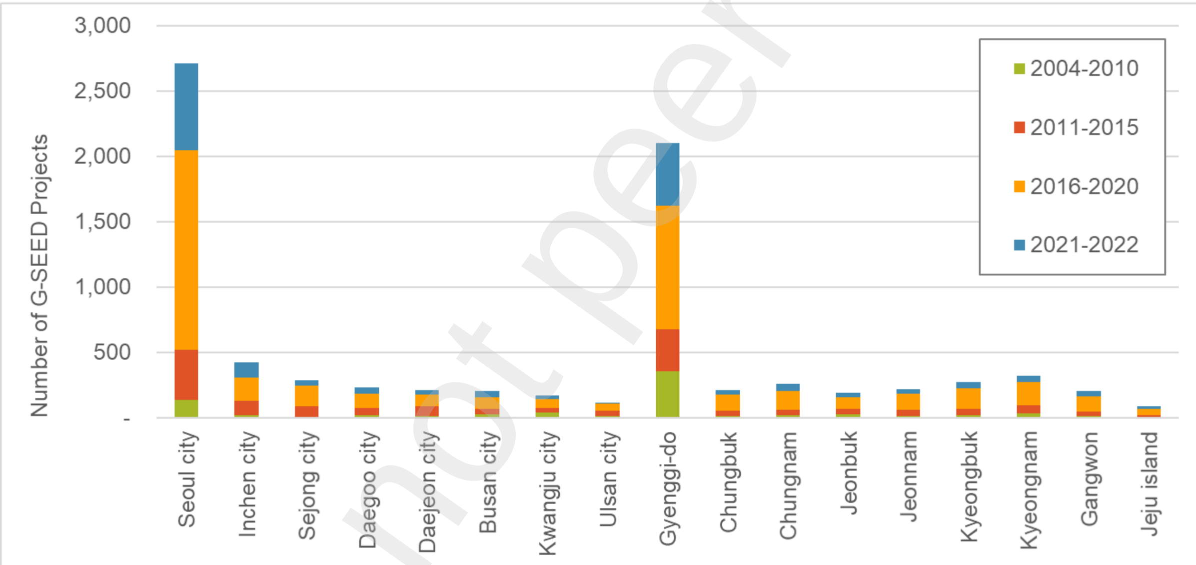


Fig. 7 Distribution of G-SEED-certified buildings categorized by city and province

3.3 G-SEED certification by building use type

Table 3 provides a breakdown of annual G-SEED-certified buildings by building use type, classified into residential buildings (detached houses, conventional houses, and apartments), non-residential buildings (office, educational, accommodation, retail, and other buildings), and complex buildings combining residential and non-residential uses within a single facility. Among certified buildings, residential buildings (2,716 projects) account for 33.1%, non-residential buildings (4,790 projects) make up 58.4%, and complex buildings (692 projects) account for 8.4%. The number of certified non-residential buildings is significantly high. The breakdown by building use type follows a similar trend to the total number of certified buildings shown in Fig. 4. Among the certified residential buildings, apartments (2,373 projects) hold the largest share (87.4%). Among the certified non-residential buildings, other buildings (1,896 projects) had the largest share (39.6%), followed by educational buildings (1,491 projects [31.1%], and office buildings (1,167 projects [24.4%]. Conversely, over 20 years of G-SEED implementation, only 210 accommodation facilities and 28 retail facilities received certification, as shown in Table 3. This indicates a small number of certified buildings in these two use categories. The number of certified detached houses among residential buildings is very small, with only six cases.

Table 3. Number of annual G-SEED-certified buildings categorized by building use type

Building type	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Residential	3	1	4	13	49	83	102	71	44	49	88	100	127	218	322	385	377	316	364
(Apartment)		1	4	13	49	83	102	71	44	49	87	100	127	206	284	306	295	250	299
(Detached house)											1	0	0	2	0	2	0	0	1
(Conventional house)														10	38	77	82	66	64
Non-residential	0	1	4	22	104	166	171	140	130	177	238	362	384	458	452	487	560	523	413
(Office)		1	3	17	10	19	33	32	32	48	73	92	75	106	98	114	141	133	140
(Educational)			1	5	91	142	134	101	81	88	88	147	126	111	84	79	96	75	42
(Accommodation)					3	3	2	3	0	2	10	29	26	36	27	34	23	8	7
(Retail)						2	2	3	1	1	2	2	2	0	0	2	4	2	2
(Other)								1	16	38	65	92	155	205	243	258	296	305	222
Complex building		1		1		2	5	7	5	15	25	78	56	72	79	100	99	101	76

4. Limitation of G-SEED

4.1 Regional distribution and gap between city and province

South Korea has regions with eight major cities and nine provinces, including Jeju Island. This study examined the number of G-SEED-certified buildings in these regions. Table 4 contains the results of the analysis on the number of buildings, G-SEED-certified buildings, and the ratio of certified buildings by region in South Korea. According to statistics on Korea's overall building status [31], there were 7,354,340 buildings in Korea in 2022. Excluding buildings not subjected to G-SEED, such as warehouses, livestock houses, and factories, the number is approximately 6,148,470 buildings. Therefore, G-SEED-certified buildings account for 0.13% of all buildings in South Korea. Among the major cities, Sejong, Seoul, and Incheon have a high proportion of certified buildings. Among the provinces, Gyonggi-do has the highest number of certified buildings. When comparing the proportion of certified buildings, large cities have approximately twice the proportion of certified buildings compared to provinces. It was found that there is a gap between the number of certified buildings in cities and provinces and the overall construction of green buildings.

The number of buildings constructed after the implementation of G-SEED is approximately 1,789,800. Based on this number, G-SEED-certified buildings account for 0.46% of this total. Given that green buildings represent approximately 0.5% of buildings constructed after the introduction of G-SEED, it is clear that despite the importance of green buildings, their adoption has not reached a significant scale. Most G-SEED-certified buildings were constructed between 2016 and 2020 in all regions. Despite the challenges posed by the COVID-19 pandemic, efforts have been made to construct a significant number of green buildings in 2021 and 2022.

4.2 Private and public buildings

Buildings owned or managed by public agencies are classified as public buildings, while all other buildings are categorized as private buildings for this analysis. The analysis of results is depicted in Fig. 8. Among the G-SEED-certified buildings, 4,527 (55.2%) are public buildings, and 3,673 (44.8%) are private buildings. These numbers provide convincing evidence that the number of certified public buildings exceeds that of certified private buildings. All three buildings certified in 2024, the first year, and the three buildings certified in 2005, the second year, were private buildings. However, from 2007 to 2015, the number of certified public buildings was more than twice that of certified private buildings each year. This shows that G-SEED initially functioned as a certification system supported by public projects. Since 2018, when G-SEED has been in operation for over 15 years, the number of certified private buildings has continuously exceeded that of certified public buildings, reflecting a considerable expansion in the awareness and acceptance of green buildings in the private building market.

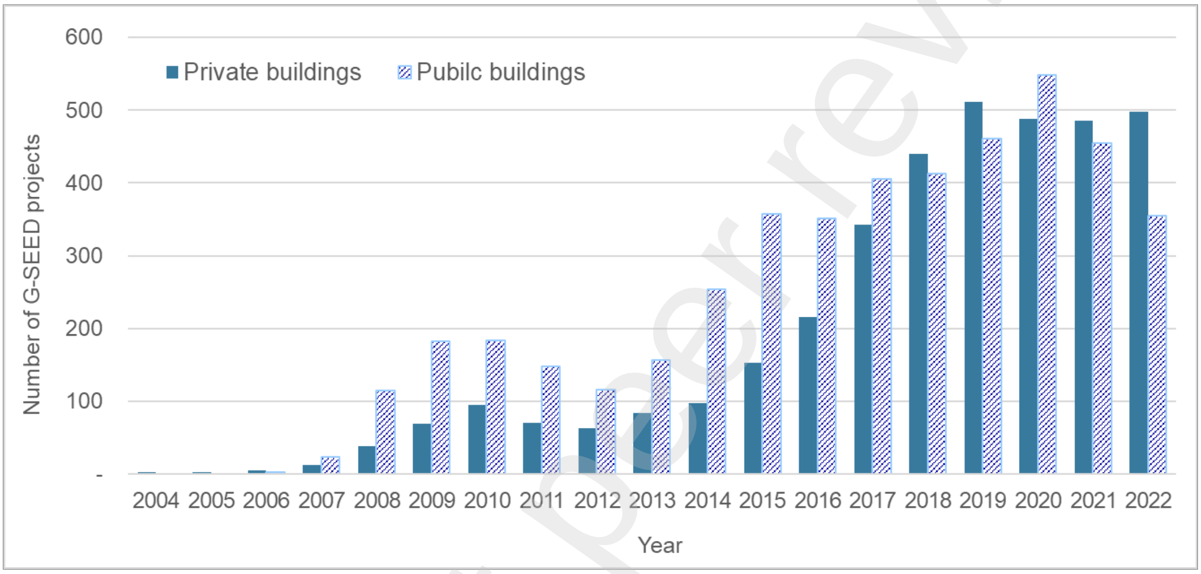
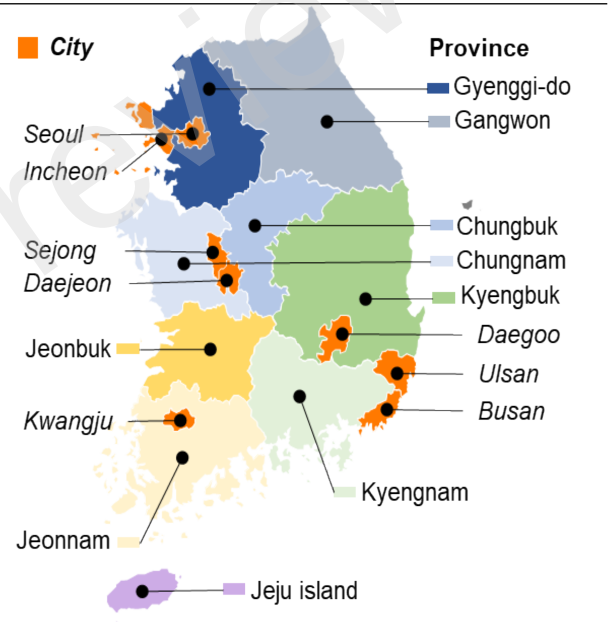


Fig. 8 Number of annual G-SEED-certified buildings categorized by building ownership

Table 4. Number of buildings and G-SEED-certified buildings categorized by city and province

Region	No. of certified buildings	Location	No. of certified buildings	No. of buildings	Ratio of certified buildings (%)	Location on the map of South Korea
City	4,343	Seoul	2,711	574,438	0.47	
		Incheon	424	192,170	0.22	
		Sejong	282	27,492	1.03	
		Daegoo	227	217,035	0.10	
		Daejeon	212	123,037	0.17	
		Busan	206	321,814	0.06	
		Kwangju	166	127,059	0.13	
		Ulsan	115	112,312	0.10	
Province	3,856	Gyenggi-do	2,098	980,553	0.21	
		Chungbuk	212	323,308	0.07	
		Chungnam	257	442,207	0.06	
		Jeonbuk	191	367,416	0.05	
		Jeonnam	216	545,055	0.04	
		Kyeongbuk	274	666,108	0.04	
		Kyeongnam	317	610,579	0.05	
		Gangwon	204	368,633	0.06	
		Jeju island	87	149,252	0.06	
(No. of total)	8,199	(Total)	8,199	6,148,468	0.13	



5. Technical characteristics of G-SEED-certified buildings

5.1 Sampling for analysis

Certification items of G-SEED evaluate the extent to which the building complies with green building technologies and how effectively eco-friendly design elements have been integrated into the building. This study analyzed the certification results for a set of 48 sample buildings certified in 2020. These data were collected through the G-SEED certification management system. Among the sample buildings, three buildings received Green 1 grade, six buildings received Green 2 grade, 11 buildings received Green 3 grade, and 28 buildings received Green 4 grade (Refer to Table 5). The green building technologies applied to the sample buildings are listed in Table 6.

Table 5. Number of sampling by G-SEED certified buildings categorized by building type

Building type	Sum	Grade			
		Green 1	Green 2	Green 3	Green 4
Total	48	3	6	11	28
Residential building	18	1	2	4	11
Non-residential building	26	2	4	5	15
Complex building	4	0	0	2	2

Table 6. Applicable technologies and their application proportion in certified sample buildings

Field category	Applicable technology in certification items	Application proportion/Average point	
		RB (a/b)	NRB (a/b)
Land use and transportation	Underground space development Use public transportation	36.7%/1.3 100%/1.35	20%/1.2 100%/0.8
Energy and pollution	Simulation for energy efficiency certificate TAB or commissioning Energy metering and energy management Energy-efficient lighting and daylight sensor Renewable energy system Cogeneration system, district heating & cooling Adjustable sun shading	100%/9.2 n/a 72%/0.86 n/a 33%/1.9 50%/0.6 n/a	100%/11.6 15.4%/0.7 42%/0.98 31%/3.6 61.5%/2.6 20%/0.6 6.3%/0.8
Materials and Resources	EPD material Recycled material Eco-label material	100%/2.9 100%/1.4 100%/1.2	100%/2.4 100%/0.8 100%/0.8
Water management	Permeable pavement Water saving appliance Water sub-metering	16%/0.6 100%/3 100%/1.6	10%/0.8 95%/3 100%/1.6
Maintenance	Manual of user or operating equipment	100%/2	100%/2
Ecological environment	Planting in buildings and land	28.6%/4.5	21.4%/5.3
Indoor quality environment	Natural ventilation Heat recovery ventilation Control of air temperature Control of indoor environmental (including temperature, ventilation, airflow, and lighting) Sound insulation & noise control	100%/1.6 100%/2 100%/0.8 n/a 96.2%/3.2	60%/1.2 10%/0.4 100%/0.8 10%/1.2 n/a

TAB, testing, adjusting, and balancing; RB, residential building; NRB, non-residential building; a/b represents the status of applicable technologies, where "a" stands for application proportion (%) and "b" represents the average points in certification items.

5.2 Land use and transportation

The criteria for land use certification items of G-SEED cover various aspects, including preserving the ecological value of the site, the ratio of underground structures, building height and shape to ensure neighboring buildings' access to sunlight, the provision of bicycle-related facilities, and the accessibility to public transport.

The assessment of underground space development considers the structural technology for underground structures, the installation facilities (e.g., machine rooms, septic tanks, and water tanks), and measures to protect groundwater.

Because underground areas often harbor diverse ecosystems and serve as conduits for vital resources such as groundwater, excessive development of underground space can degrade the environment and deplete valuable resources. However, in densely populated large cities, the development of underground spaces is essential. Since many buildings constructed in large cities are certified, the application of this certification item is not very widespread.

Assessing public transportation usage includes determining the proximity of easily accessible public transportation, such as buses, subways, and trains, to the target building. All certified sample buildings had access to at least one form of public transportation, as shown in Table 6. Measuring public transportation does not directly reflect the buildings' performance; rather, location becomes an important factor. Using public transportation offers notable benefits, including reductions in fossil fuel consumption, atmospheric particulate matter (PM), and pollutants. Therefore, it is essential to consider access to public transportation when planning a building project.

5.3 Energy and pollution

Building energy efficiency is considered important in many green building certification systems [39]. Energy performance in G-SEED is the most important evaluation item among the detailed certification items [14,22]. As depicted in Table 1, energy performance carries a weight of 12 points, which is higher than other detailed certification items. To achieve a high certificate grade, a high score in energy performance is required. G-SEED evaluates energy performance using two methods. The first method is the energy performance index (EPI), which is based on the Building Energy Conservation Code (BECC) [30]. For EPI, architecture, equipment, electricity, and renewable energy technologies are evaluated, with scores assigned according to the specifications of each design element without building energy simulations. It further evaluates whether the requisite conditions are met using a comprehensive checklist. The other method is based on the building energy efficiency rating (BEER) [32]. In Korea, BEER is categorized into ratings ranging from 1+++ to 7 based on the annual primary energy consumption of a target building. To achieve high BEER ratings, buildings must incorporate highly insulating envelopes and high-efficiency equipment into their construction and design [32,33].

All sample buildings in this study achieved high energy performance scores. Among the sampled residential buildings, only one met the EPI score requirements, whereas the remaining samples received their scores through

BEER ratings. G-SEED certified buildings with Green 1, Green 2, and Green 3 grades received BEER ratings of 1 and 1+. In the non-residential building sample, two buildings met the energy performance criteria based on the EPI score, whereas other buildings derived their scores from BEER ratings 1+ or higher.

Testing, adjusting, and balancing (TAB) and commissioning processes for heating, ventilation, and air-conditioning (HVAC) systems are exclusively evaluated in non-residential buildings. These evaluations are procedures for verifying and adjusting whether a building is functioning in accordance with the performance requirements of the building design, including adjustments that affect building performance and efficiency. Approximately 15.4% of the sample buildings performed TAB or adjusted buildings through TAB and commissioning.

Building energy monitoring is a crucial practice that involves tracking the consumption of individual energy sources, such as electricity, gas, and oil, or measuring the consumption of individual energy sources, such as cooling, heating, hot water supply, lighting, ventilation, electric heating, and pumps. In residential buildings, approximately 72% of sample buildings monitor the consumption of each energy source and communicate this information to occupants and building managers for effective management of the building's energy consumption. For non-residential buildings, 42% have implemented energy monitoring and management systems. Green 1-graded buildings were found to have comprehensive energy management systems, which, in addition to monitoring energy consumption, also include functions for analyzing building energy consumption and controlling HVAC equipment.

Daylight sensors and high-efficiency lighting, such as LEDs, are evaluated as detailed certification items in office, educational, and retail buildings. Remarkably, 30% of the sample buildings had energy-efficient lighting designed for an illuminance ranging from 5.07 to 9.0 W/m^2. However, G-SEED does not evaluate residential buildings for the use of high-efficiency lighting.

The use of district heating systems is effective in reducing GHG emissions and air pollution, primarily owing to their superior energy efficiency compared to other heating methods. The Korean government has made efforts to expand district heating in buildings. The residential district heating penetration rate was 17.6% in 2018, with a target of reaching 20.9% by 2023 [34]. Among the certified sample buildings, 50% of residential buildings and 20% of non-residential buildings used district heating as an energy source.

In South Korea, buildings offering an outside view are preferred. Curtain walls have a higher window-to-wall ratio (WWR) compared to other envelope structures, largely due to the high proportion of windows. High WWR can lead to increased internal heat loss in winter and increased cooling load in summer, as solar heat enters interior spaces through windows. To counter these effects, adjustable sun shading systems that effectively block solar heat from entering through windows have gained popularity. In a building model with a WWR of 45%, the installation of external blinds can reduce cooling energy requirements by 3.5% [40]. The Korean government also recommends installing external shading, as outlined in the BECC [30].

5.4 Materials and Resources

Sustainable materials and green building materials play an important role in reducing building energy consumption and embodied GHG emissions [35]. Green building materials also contribute to improving the quality of the indoor environment. These materials include ecological materials, recycled materials, certified eco-friendly materials, low-carbon materials, and materials with reduced harmful substances. As indicated in Table 6, all certified sample buildings used environmental product declaration (EPD) materials, recycled materials, and eco-labeled materials. Residential buildings used more green building materials than non-residential buildings.

The environmental impacts of buildings can be reduced by using EPD materials for major building materials. This is because EPD materials undergo a thorough evaluation and quantification of environmental impacts during the production, usage, and disposal phases through a life cycle assessment (LCA) process. For the sample buildings, five to seven EPD materials were used for major elements such as structures, exterior walls, roofs, and floors. The certification grants a minimum score of 0.8 points when incorporating seven or more recycled materials and a maximum score of 2 points when using 25 or more recycled materials. Korea's MOE certifies eco-label materials through the eco-labeling certification mark [36]. G-SEED evaluates the use of building materials bearing these eco-labels, considering the quantity of such materials used during construction.

5.5 Water management

The assessment of water management is closely linked to the proportion of permeable surfaces within the external site area. This ratio bears significance in evaluating external factors such as rainwater management and groundwater protection. The external property area is calculated by subtracting the natural ground area from the total property area. G-SEED provides a score when the proportion of permeable pavement exceeds 50%. Pavements are considered permeable if the thickness of the pavement layer and the filling exceeds 20 cm, or if the thickness of the vegetation layer exceeds 20 cm in the case of planting.

Efforts to save water in buildings are widespread in green buildings. G-SEED allocates points when water-saving faucets or toilets are used throughout the building, with scores determined based on annual water savings compared to annual water consumption. Installing water consumption monitoring devices reduces unnecessary water consumption and promotes efficient management by making water supply in the region available to users and managers through meters. In residential buildings, water consumption monitoring devices must measure all household water consumption in real-time. In non-residential buildings, water consumption monitoring devices must measure the water consumption of the entire building based on the usage and the management area. Additionally, eco-labeled products are required for all water consumption monitoring devices.

5.6 Maintenance

Effective building maintenance is paramount to conserving energy and resources. In G-SEED's maintenance field, the evaluation focuses on whether methods of operation and management of the technologies used in other field categories are presented to users and managers, rather than on the technical aspects of green buildings. Basic requisites include inspection manuals for as-built drawings and detailed equipment, as well as equipment and product usage manuals. Given the wealth of manuals and catalogs available for products and equipment, all the sample buildings succeeded in this category.

5.7 Ecological environment

Technologies for securing planting spaces within buildings include various aspects such as areas on natural ground, permeable pavements with plants, and the greening of roofs and exterior walls. Building roofs serve as preferred locations for greenery. Plantings also extend to the exterior walls and surrounding landscaping of buildings.

Plantings can be introduced in building construction projects to reduce cooling/heating energy consumption, respond to climate change, and absorb carbon. However, roofs have multiple functions, serving as recreational spaces, hosting renewable energy sources (e.g., PV and solar thermal systems), external lighting, and promotional signboards. This limits the available planting space on roofs, increasing the demand for vertical planting on exterior walls. For non-residential buildings where securing external planting space is challenging, the focus shifts to integrating ecological functions into the building interior.

5.8 Indoor quality environment

In 2021, the annual average PM (PM10) concentration in Korea was 36 μg/m^3, more than twice the recommended limit of 15 μg/m^3 set by the World Health Organization (WHO) [37]. Growing concerns over PM pollution and yellow dust have heightened the demand for improved ventilation systems in buildings. Furthermore, the emergence of infectious diseases, such as COVID-19, also highlights the importance of ventilation. Technologies that meet this demand include operable windows and mechanical ventilation systems with heat recovery capabilities. The evaluation criteria for natural ventilation are based on the ratio of the opening area of windows to the floor area. A score is awarded if the ratio exceeds 8% for residential buildings and 2% for non-residential buildings. Waste heat recovery systems are suitable for residential buildings in winter when there is a significant temperature difference between indoor and outdoor environments, aligning with the BECC recommendations [30]. Ventilation systems with heat recovery for residential buildings were used in all households in the sample buildings. However, in non-residential buildings, using waste heat recovery systems in mechanical ventilation systems can be relatively difficult due to the prevalence of central air conditioning systems.

Giving residents the ability to control indoor temperatures using automatic temperature controllers increases comfort and saves energy on heating and cooling. Residential buildings are evaluated based on the installation of an automatic temperature controller connected to the heating system. The percentage of the total area that can be adjusted for heating and cooling by installing temperature sensors in each room or zone is assessed for non-residential buildings. The evaluation includes whether occupants can control the indoor environment, including ventilation volume and lighting, as well as the indoor temperature of the workspace. The area where individual control is possible must not exceed 20 m^2 to score points on G-SEED. The noise environment is only assessed in residential buildings. The evaluation includes factors such as the impact of sound insulation performance on the floor, sound insulation performance between households, outdoor noise insulation performance, and sound insulation in the bathroom [26].

6. Recommendations and discussion

This study analyzed the status of G-SEED, a Korean green building certification system that has been implemented for over 20 years with the aim of promoting green buildings. We also analyzed the technical aspects based on certified buildings. Based on these analyses, several proposals are presented for the promotion of green buildings:

6.1 Strengthening awareness for green buildings

New buildings have predominantly achieved the Green 4 grade, followed by Green 2, Green 3, and Green 1 grades. Numerous public buildings have obtained the Green 2 grade, as it is a requirement during construction. Future policies and incentives should be designed to ensure buildings receive higher grades when they receive G-SEED certification. Following this, the Korean government must encourage the construction market to build more buildings with lower energy consumption and GHG emissions, as well as higher environmental performance.

The benefits of green buildings, such as sustainability, energy saving, environmental protection, improving comfort, and increasing building value, are not well known. Various measures should be taken to raise awareness of green buildings among designers, owners, and users of buildings. An appropriately established set grade of green building certification can provide green buildings with reliability and a quantitative index of performance.

6.2 Need to revise certification criteria of G-SEED

The central area of the Korean Peninsula is the most important region for G-SEED certifications. The cities and provinces with the largest number of certified buildings are Seoul and Gyeonggi-do. Both Seoul and Gyeonggi-do belong to the central region. As shown in Table 4 and Fig. 7, all major cities and local governments in Korea have G-SEED-certified buildings, indicating a nationwide presence and growing awareness of green buildings.

However, the number of certified buildings remains relatively small compared to the entire building stock. To foster more interest, increased promotion and marketing of G-SEED, as well as the popularization of green buildings, are required. The Korean government should consider incorporating regional characteristics or contents into G-SEED certification criteria.

Among residential buildings, apartments have received the most certifications, whereas educational and office buildings have received the most certifications among non-residential buildings. Many buildings were constructed with spaces for different uses, contributing to the overall increase in G-SEED-certified buildings. However, the number of G-SEED-certified detached houses, accommodation facilities, and retail buildings is very small. For future revisions of G-SEED, the Korean government should carefully consider whether the certification items and evaluation criteria for accommodation facilities, retail, and detached houses are appropriate. Moreover, to further promote green buildings, the government should consider providing separate incentives and cost-optimized technologies to generate interest in green buildings within these specific building use categories.

6.3 Recommendations for the application of green building technology

Among the green building technologies applied to G-SEED-certified buildings, the use of public transportation, energy efficiency, green building materials, water-saving equipment, heat recovery ventilation systems, and automatic indoor temperature controllers was consistent across all sample buildings in this study. Building energy efficiency, particularly, proves to be the most critical evaluation item. This is due to the need to achieve high energy performance scores with many points awarded in order to obtain higher certificate grades. Technologies such as high-insulation envelopes, high-efficiency equipment, high-efficiency lighting, and renewable energy systems have been used to improve building energy efficiency and help reduce energy consumption. When selecting technologies to be used for a green building, these technologies should be able to reduce the actual energy consumption of buildings and contribute to the sustainable development of green buildings, and not just be selected for a high certification grade. Green buildings should maintain the original technical functions of the applied technologies during the operational stage of buildings. Therefore, it is necessary to highlight the certification items for the energy monitoring and management system so that the impacts of the use of these technologies can be examined in the operation stage of the building.

Certification items focusing on the use of green building materials are also important evaluation items. All sample buildings used EPD materials, recycled materials, and eco-labeled materials. Since the number of green building materials used in a building is an evaluation criterion in G-SEED, there are limitations in evaluating environmental performance as well as embodied energy and GHG according to the construction materials used in the building. Other green building certification systems, such as LEED, BREEAM, and CASBEE, have evaluated GHG emissions linked to construction materials by incorporating LCA criteria since 2009. Consequently, it has been suggested that G-SEED should also include evaluation criteria for the GHG emissions of key construction materials [38]. As the significance of sustainable construction materials increases in green buildings, the inclusion of LCA criteria becomes imperative for certification systems.

The technologies applied to green buildings include the seven field categories of G-SEED. Consequently, certain technologies have found limited application. Future revisions of G-SEED should consider a broader range of technologies for green building implementation in certification evaluation items. A potential solution could be to assess the complexity of technologies and the excellence of their performance, assigning weights to different evaluation indicators.

7. Summary and Conclusion

The assessment and rating of green buildings or sustainable construction is a global concern in both developed and developing countries [39]. As buildings demand high energy and resource consumption, green buildings are also highlighted in Korea as a key strategy to reduce GHG emissions [10]. South Korea has been striving to build and promote green buildings for 20 years, operating G-SEED as its representative green building rating system. G-SEED evaluates buildings using 46 detailed certification items categorized into seven field categories, as shown in Table 1. These detailed certification items evaluate aspects of building planning and technologies essential for achieving green buildings' performance standards. This paper reviews G-SEED and the status of certified buildings in South Korea. This article also examined the limitations of G-SEED and analyzed the technical characteristics of G-SEED-certified buildings. Following these reviews and analyses, this paper presented proposals for expanding green buildings and revising the G-SEED certification system. These proposals provide meaningful insights for decision-makers operating green building certification systems in other countries.

The results of this study show that the number of G-SEED-certified buildings has steadily grown, reaching 8,200 by 2022. In the early stages of Korea's green building certification, the focus was primarily on public buildings. Following the passage of Korea's Green Buildings Construction Support Act [8] in 2012, which expanded G-SEED's target scope to all building uses, the number of certified projects has significantly increased. Additionally, G-SEED-certified buildings are now being constructed in all cities and regions in South Korea. Based on the analysis of sample buildings, this paper also provided the technical characteristics of G-SEED-certified buildings and technologies used to evaluate them as green buildings. The most commonly adopted technical features included the use of public transportation (such as buses and bicycles), energy efficiency technologies, eco-friendly materials, water-saving appliances, operational manuals, and ventilation systems with heat recovery and air temperature control. This paper could help architects, building owners, and researchers in gaining a comprehensive understanding of G-SEED. Readers can understand the technical level of green buildings through this study.

However, there are some limitations to the role of green building certification in the spread of green buildings. Among the buildings certified in South Korea from 2004 to 2022, 50% received a Green 4 grade, the highest proportion. To increase the sustainability of the project and achieve a reduction in GHG emissions, it is necessary to design buildings targeting a higher Green 2 grade or higher. Current data from the results of this study show that only a small proportion of the building stock has achieved green building certification. For public buildings, obtaining green building certification through G-SEED evaluation is mandatory, while for private buildings, certification is voluntary. To strengthen the role of G-SEED in promoting green buildings in the private real estate market, the Korean government and the managing authority of the certification system should continuously improve G-SEED. Various measures, such as incentives and tax exemptions, should be continuously proposed to accelerate green building in private construction companies. Recently, attempts have been made to extend G-SEED certification to overseas green buildings. Insights from international green building certification systems in more advanced countries can prove invaluable in this endeavor.

Green buildings are considered key enablers of sustainable cities and society, and the green building certification system has played a significant role in their development. Green buildings should be continuously promoted globally, and more research on these topics should be conducted in the future.

Glossary

Green Building Certification: A system that assesses and rates the sustainability and environmental performance of buildings.

Green Standard for Energy and Environmental Design (G-SEED): South Korea's green building certification system designed to promote sustainable development and reduce greenhouse gas emissions.

Greenhouse Gas (GHG): Gases in Earth's atmosphere that trap heat, contributing to global warming and climate change. Common GHGs include carbon dioxide (CO_2) and methane (CH_4).

Sustainable Development: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs, focusing on environmental, economic, and social sustainability.

Certification Criteria: The set of standards and requirements that a building must meet to obtain a particular level of green building certification.

Accredited Evaluation Agencies: Organizations authorized by the government to assess and certify buildings based on the green building certification criteria.

Pre-certification: The initial stage of green building certification, where a building's design and planning documents are evaluated before construction begins.

Main Certification: The final stage of green building certification, conducted after the construction of the building, involving on-site inspections and a review of the completed project.

Field Categories: Specific areas of focus within the green building certification system, such as land use, energy efficiency, water management, and indoor environmental quality.

Detailed Certification Items: Specific criteria within each field category used to evaluate various aspects of a building's environmental performance.

Low-Carbon Energy Source Technology: Technologies that generate energy with significantly lower emissions of carbon dioxide compared to conventional fossil fuels.

Environmental Management Plan: A plan that outlines procedures and measures to minimize the environmental impact of a construction project.

Biotope: A specific area with uniform environmental conditions providing a habitat for a particular group of plants and animals.

Renewable Energy: Energy generated from natural resources that are replenished constantly, such as solar, wind, and hydroelectric power.

Ecological Value: The importance of a land area based on its ability to support biodiversity and provide ecosystem services.

Green Remodeling: The process of upgrading an existing building to improve its energy efficiency and environmental performance, making it more sustainable.

Platinum, Gold, Silver, Bronze Certification Grades: These represent different levels of achievement in the green building certification process, with Platinum being the highest and Bronze the lowest.

Testing, Adjusting, and Balancing (TAB): Procedures conducted on building systems, such as HVAC, to ensure they operate efficiently and effectively according to the design specifications.

Energy Performance: A measure of how efficiently a building uses energy, typically evaluated in terms of energy consumption per unit area.

Rainwater Management: Systems and practices designed to collect, store, and utilize rainwater for various purposes, reducing the demand for potable water and minimizing runoff.

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Declarations of 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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