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Review

Status of Environmental Life Cycle Assessment (LCA): A Case Study of South Korea

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Abstract: The Life Cycle Assessment (LCA) as an environmental-impact assessment tool has received increasing attention over the years. Unlike the water footprint (WF) and carbon footprint (CF) assessments, whose focus is only on a single environmental aspect, the LCA systematically analyzes the different impacts along the entire life cycle, making possible the identification of potential environmental tradeoffs. In Korea, LCA has drawn much attention from both industry and academia since the mid-1990s. However, the level of Korean-related LCA studies with respect to different sectors in the last 20 years has not been analyzed. This study, therefore, sought to assess the status of environmental Life Cycle Assessment (LCA) studies in South Korea. Specifically, the study focused on a bibliometric review of LCAs conducted in South Korea in the last 20 years and identified potential research gaps. Online searches of English-written articles published between 2000 and 2019 were conducted on Google, Google Scholar, Scopus, and Web of Science databases, using eligible keywords. At the end of the search, about 91 LCA-related studies were discovered for South Korea within the study period. The majority of these studies focused on the construction (47%) and energy (30%) sectors, with fewer environmental studies on manufacturing (11%), transportation (9%), agriculture (2%), and information and communication (1%) industries. Based on publication trends, results show that LCA studies in South Korea have been on the rise in the past 20 years, even though the number of publications has not followed a constant pace. In comparison with the economic sectors of the country, reports show an inadequacy in the coverage of major industries of growing economic relevance, such as tourism, health, and agriculture, suggesting a need to increase and improve LCA-related studies in these sectors.

Keywords: Life Cycle Assessment (LCA); environmental impact assessment; sustainability reporting; Korea

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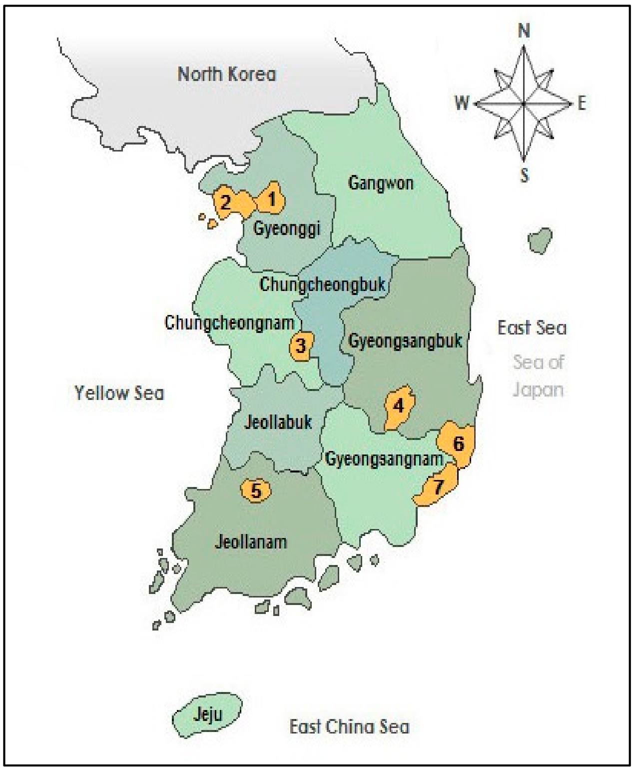
1. Introduction

The Life Cycle Assessment (LCA) as an environmental-impact assessment method is gaining increasing attention all over the world due to the urgent need for the preservation and sustainability of the environment. Commonly utilized in the environmental analysis of businesses, industries, products, and services, this assessment method promoted by the United Nations Environment Programme (UNEP)/Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative, the Forum for Sustainability through Life Cycle Assessment (FSLCI), International reference Life Cycle Database System (ILCD), the European reference Life Cycle Database system (ELCD), and a host of others aims at improving environmental performance towards the achievement of economically viable, safe, and sustainable societies. The Life Cycle Assessment technique is an important means of identifying the environmental impact of products or services throughout their entire life cycle stages [1]. These life cycle stages normally include raw-material extraction, processing, transportation, use, and disposal or recycling. The systematic analysis of the different impacts along the entire life cycle makes possible the identification of potential environmental tradeoffs between stages [2]. This makes the LCA approach different from other assessment methods, such as the water footprint (WF) and the carbon footprint (CF), whose focus is only on a single environmental aspect.

With a population of more than 4.5 billion people (about 60% of the world population), Asia is the fastest growing economic region in the world in terms of nominal GDP and Purchasing Power Parity (PPP) [3]. South Korea with a population of about 51.71 million people, is amongst the top 10 economies in Asia, and is also part of the top 3 economies in East Asia [3]. Geographically, it lies between latitudes 33° and 39° N, and longitudes 124° and 130° E. Occupying the southern part of the Korean peninsula, the country has a total area of 100,032 km^2 which is mostly mountainous. The country also tends to have a humid continental and subtropical climate, comprising four different seasons (spring, summer, autumn and winter) with heavy precipitation and hot and humid temperatures (exceeding 30 °C) in the summer months, and extremely cold temperatures (dropping as low as −20 °C) in the winter months. South Korea operates a mixed economic system heavily dependent on international trade with export and import of goods and services accounting for 44.01% and 38.99% respectively [4]. The country's largest industries are the manufacturing, trade, and construction respectively [5] (Figure 1b). South Korea also produced more than 553 terawatt hours (TWh) of gross electricity in 2017, based on estimations by the Korea Energy Economics Institute [6].Two-thirds of this electricity generation is accounted for by fossil fuel sources, with almost one-third being accounted for by nuclear sources. Presently, South Korea sits as one of the highest carbon dioxide emitters in the world [7]. By ranking, it is the 9th largest electricity consumer and the 7th largest CO_2 emitter [8]. This is largely due to the highly industrialized nature of the country characterized by energy-consuming activities, as well as the surging population over the years, which are hugely contributing to the increasing environmental problems in the country [9]. As environmental concerns increase, the need for environmental data management also increases. Hence, in an effort to curtail environmental challenges, the Korean government over time has encouraged sustainable environmental and economic research in all scientific fields through the increased funding of Research and Development (R&D) projects (Figure 2).



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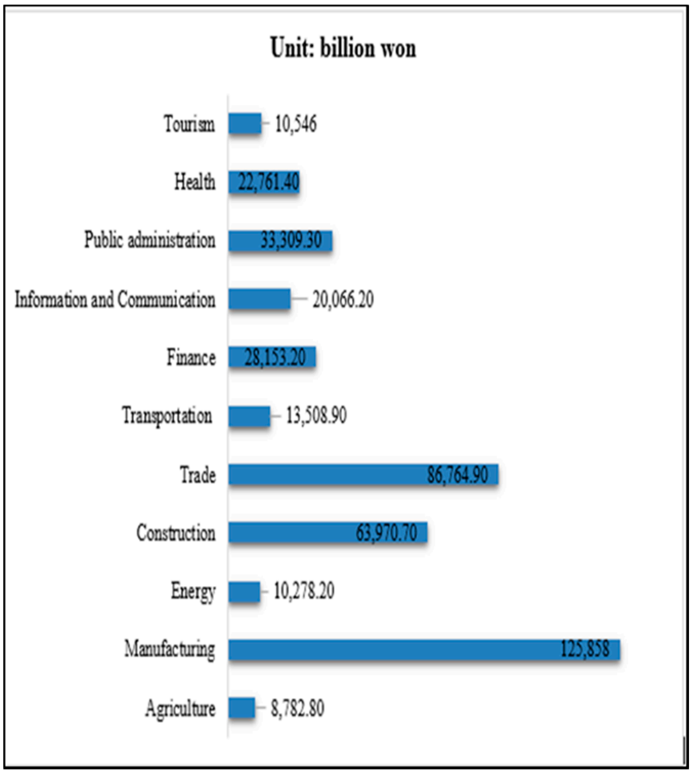

(**b**)

Figure 1. (**a**) Map of South Korea (adapted from https://www.gone2korea.com/ (accessed on 11 September 2020); 1—Seoul, 2—Incheon, 3—Daejeon, 4—Daegu, 5—Gwangju, 6—Ulsan, 7—Busan). (**b**) Korea's Major Economic Sectors by Gross Domestic Product (GDP) (2020 report).

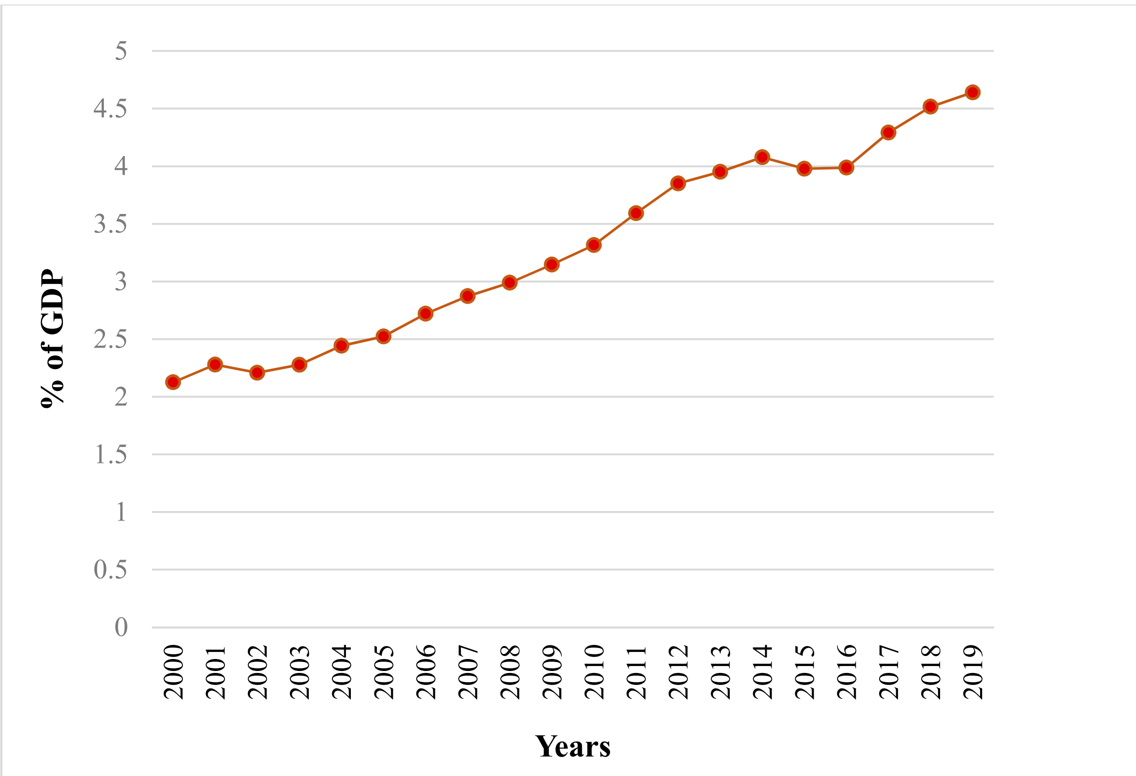

Figure 2. Gross Domestic Spending on R&D (2000–2019) [10].

Several reviews exist which assess the availability of LCA studies in different countries, e.g., New Zealand [11], Sweden [12], Austria [13], Portugal [14], Brazil [15], Ghana, Ivory Coast and Nigeria [16]; and continent, e.g., Africa [17]. These studies primarily focused on the quantification of available life cycle studies, in order to determine the state of sustainability reporting and identify possible research gaps. While it is known that environmental research in Korea has developed over the years, and researchers in Korea have applied the LCA techniques in several sectors since the mid-1990s [18], the extent of reporting of such Korea-related LCA information is not evident. In other words, there is no available literature on the status of LCA studies in South Korea. Hence, this paper focused on a bibliometric review of LCAs conducted in South Korea in the last 20 years, with a view to quantitatively summarizing and comparing the development process of LCA research in the country, as well as identifying possible future research areas. Studies of this nature are necessary to identify similar research needs in a country, and serve as background information in other LCA studies. Specifically, the present bibliometric study objectively reflects the development process and research focus of Life Cycle Assessment in South Korea. It shows the current tendencies and weaknesses of the research area and serves as reference for researchers and decision-makers alike.

2. Methodology

The methodology of [11] was employed with slight modifications in the search and classification of studies. A typical non-academic search was initially performed via Google and Google scholar search engines. This was followed by an academic search via the Scopus and Web of Science (WOS) bibliographic databases. These two search strategies were employed with the assumption that all literatures available will be incorporated. Non-exclusive searches were conducted using the keywords "life cycle assessment", "lca", and "Korea", to find the various articles, conference papers, and reports containing these keywords published between the years 2000 and 2019. To ensure a significant coverage of reports from the country, possible LCA studies from the major Korean companies (available at: [19]) were also searched using the same keywords as stated above, with the inclusion of "[Korean company name]". Results were restricted to only studies written in English to limit the search. Since South Korea is a non-English speaking country, it was expected that Korean-language published documents might have been available. Nonetheless, these documents were not included in this review, as LCA practitioners from the international scene may not have access to them and as such may not reliably represent a measure of LCA information from the country. In addition, the study included reports specific to activities within South Korea only.

Furthermore, this study focused on the availability of environmental Life Cycle Assessments. Other assessment studies, such as Social Life Cycle Assessments (S-LCA), which involve assessing the social and sociological aspect of a product with respect to its positive and negative impact along the life cycle, as well as life cycle costing (LCC), involving the estimation of how much money is spent on an asset in the course of its useful life, were out of the scope of this study and were thus not included. The authors would also point out that in the course of the search, reports treating only carbon and water footprints were discovered but were not included in this study; they are attached as Supplementary Materials Tables S1 and S2. The Global Reporting Initiative (GRI) sustainability report (year 2017) for South Korea (available at: [20]) was also taken into consideration. This was to ascertain the level of sectorial environmental assessment reporting from the country. The GRI report is important as it reflects the level of environmental, economic and societal consciousness of different sectors/organizations in a country [12]. The methodological process applied in this study is summarized in Figure 3.

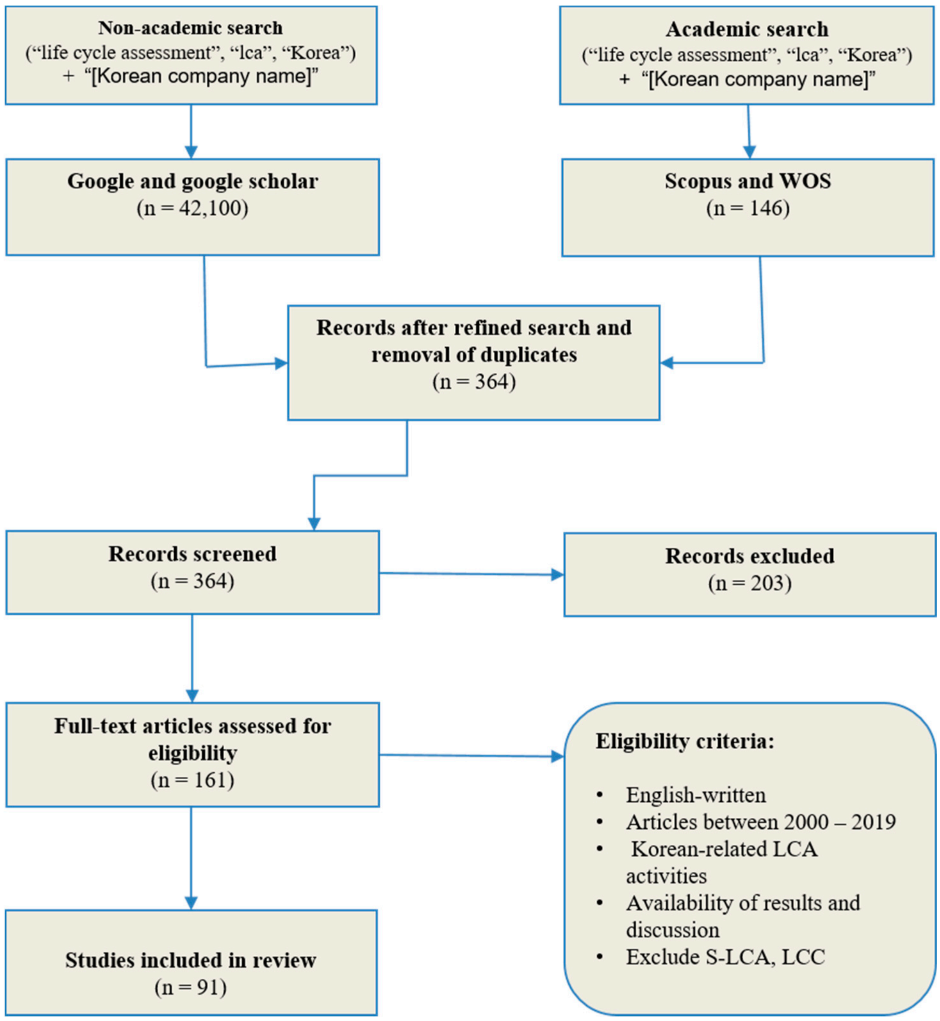

Figure 3. Flowchart indicating identification and selection of studies.

3. Results

3.1. Overview

The analysis conducted yielded 91 Life Cycle Assessment studies for South Korea. This is the highest number recorded, when compared with available related studies from other countries, implying a high level of LCA awareness in the country (Table 1). Figure 1b also shows the major sectors of Korea's economy according to Gross Domestic Product (GDP) data of 2020 [21]. It was observed that the quality of search results reduced after the first three pages of google search after which the likelihood of having repeated studies presented by different web platforms increased. This confirmed a similar observation by [12]. Based on search results, four articles were discovered for years between 2000 and 2004, sixteen were discovered between 2005 and 2009, twenty between 2010 and 2014, and fifty-one between 2015 and 2019. It can be observed that, even though the number of studies has not followed a constant pace over the years, LCA studies have received significant recognition and have been on the rise (Figure 4). This is evident from the fact that a majority of the research studies were conducted by Korean researchers in Korean research institutions within the country.

Table 1. Related studies on the availability of LCA.

Country	Period Covered (Years)	Major Industries by LCA Coverage	Number of LCA Articles Discovered	References
South Korea	2000–2019	Construction, Energy, Manufacturing, Transportation, Agriculture, ICT	91	Own elaboration
Brazil	2000–2016	Energy, Agriculture, Manufacturing, Education	73	[15]
South Africa	2000–2020	Energy, Agriculture, Construction	43	[17]
Portugal	2001–2015	Pulp and paper, Building materials, Forestry, Automotive, Energy, Transportation	28	[14]
Egypt	2000–2020	Energy, Construction, Agriculture, Transportation	23	[17]
Austria	2000–2016	Energy, Material production, Construction, Food	15	[13]
New Zealand	2006–2015	Trade, Agriculture	14	[11]
Nigeria	2000–2020	Energy, Agriculture, Construction	14	[17]
Sweden	1995–2015	Energy, Material production, Food	13	[12]
Ghana	2000–2020	Agriculture, Energy, Food, Construction	9	[17]

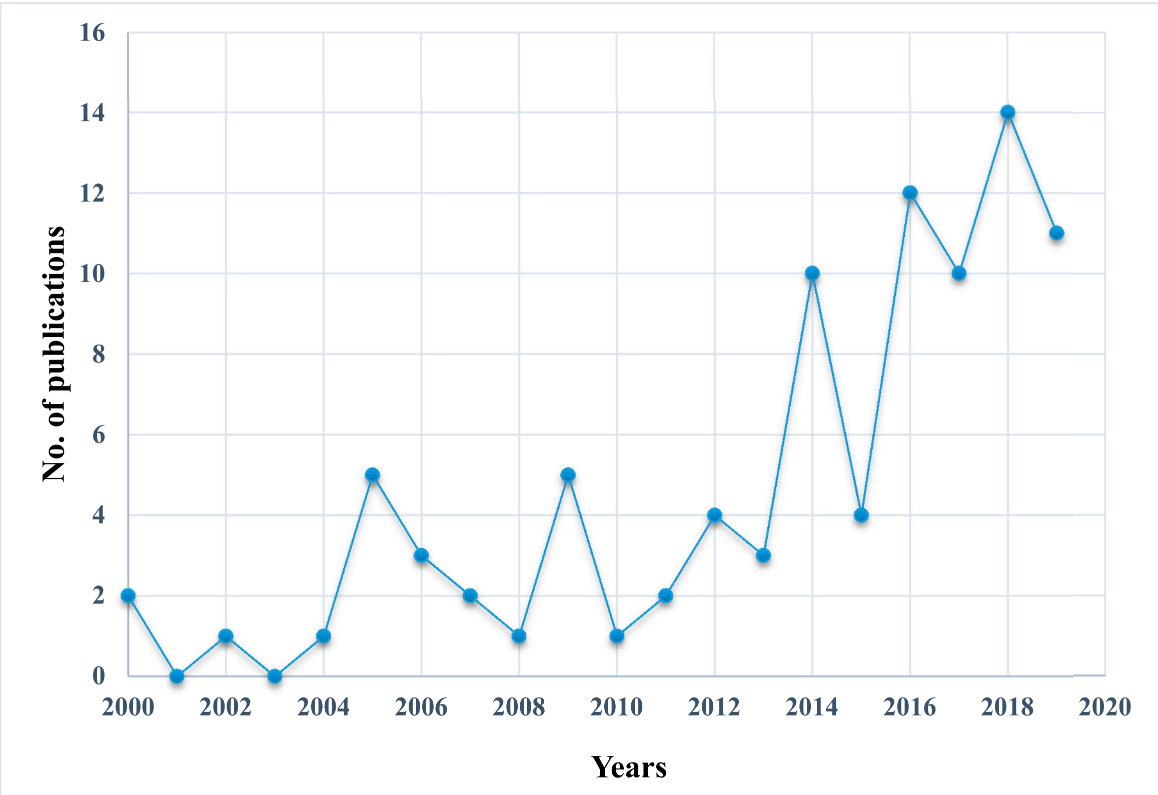

Figure 4. Trend of South Korea's publications per year (2000–2019).

Based on the sectorial contribution to LCA research, the construction sector, with the third highest contribution to the GDP, had the most LCAs available with forty-three studies. This is understandable, since Korea has mechanized several of its public works over the years, thereby consuming about 40% of total industrial energy consumption and generating large amounts of environmental emissions especially from construction sites and equipment [22], which have led to strong demands for studies on environmentally friendly construction procedures and materials. The energy sector followed closely with twenty-seven articles, which was expected, since Korea is working hard to balance its high-emitting industrial capability with "green" energy production. The manufacturing sector was next with ten studies, the transportation sector with eight studies, the agriculture sector with two studies, and the information and telecommunications sector with one study available (Figure 5). In addition, a majority of the contributions were from academic sources, especially from Hanyang University, Konkuk University, and Seoul National University; there were some contributions also from industrial sources, such as LG Electronics, Samsung Electronics, Kia Motors Corp., and Super-Tall Building Global R and BD Centre. While Table 2 provides a summary of South Korea's Sustainability GRI reports, Table 3 provides a brief description of each LCA study. Important information concerning each research article such as the product, sector, impact categories, important findings (results), and references is provided.

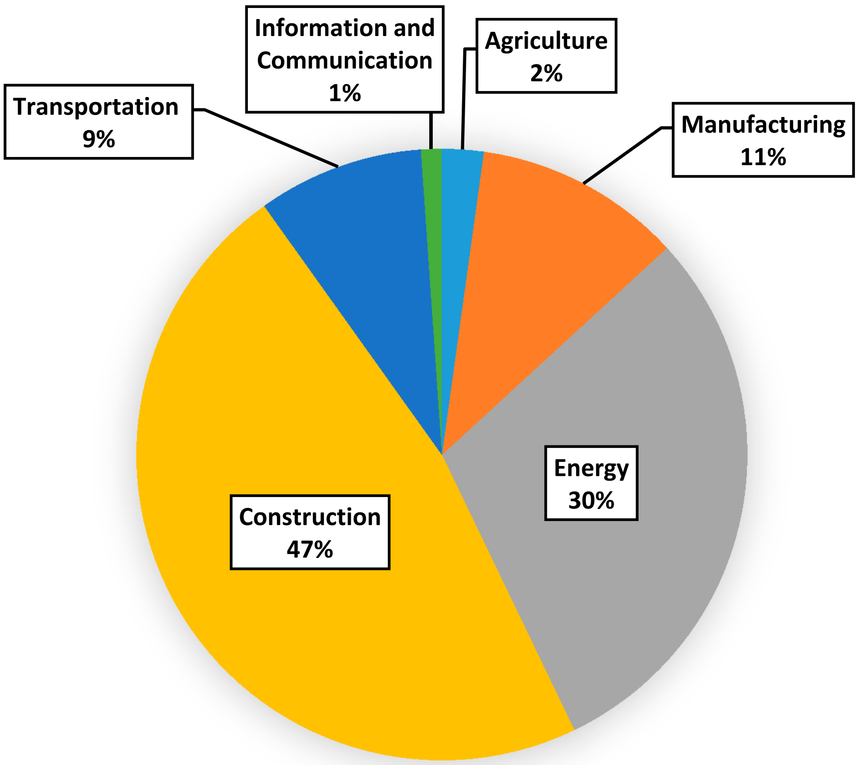

Figure 5. Classification based on LCA-related studies for various sectors.

Based on GRI sustainability reporting, the database search produced 67 reports from a number of diverse industries within South Korea (Table 2). The search included all reporting criteria of GRI-1, GRI-2, GRI-3, GRI-3.1, GRI-4, non-GRI, GRI-standards, and GRI-cited [20]. Fifty-eight of these reports were GRI-G4, five were GRI-standards, three were non-GRI, and one was GRI-cited. With respect to sector, the financial industry recorded the highest number with 11 reports. This was followed by the construction industry, with eight; the energy and automotive industries with five each; the chemicals, equipment, non-profit/services, other, and technology hardware industries with four each; the telecommunications industry with three; the conglomerates, healthcare products, and household and personal products industries with two each; and the aviation, construction materials, consumer durables, food and beverage products, logistics, public agency, railroad, textiles and apparel, and tourism/leisure industries each having only one report. The GRI report indicates the significant existence of similar environmental analysis on several sectors of the Korean economy.

Table 2. Summary of South Korea's Sustainability GRI reports available for 2017.

Sector	GRI-G4	GRI-Standards	GRI-Referenced	Non-GRI	Total
Automotive	5				5
Aviation	1				1
Chemicals	4				4
Conglomerates	2				2
Construction	5	2		1	8
Construction Materials	1				1
Consumer Durables	1				1
Energy	4	1			5
Equipment	3			1	4
Financial Services	10	1			11
Food and Beverage Products	1				1
Healthcare Products	1		1		2
Household and personal products	2				2
Logistics	1				1
Non-Profit/Services	4				4
Other	3			1	4
Public Agency		1			1
Railroad	1				1
Technology Hardware	4				4
Telecommunications	3				3
Textiles and Apparel	1				1
Tourism/Leisure	1				1
Total	58	5	1	3	67

3.2. Construction-Related LCA Studies

The LCA studies relating to the construction sector has received great interest in Korea and covers mainly environmental impacts of building and building materials, dams and bridges, and road construction.

With respect to building and building materials, Kim and Tae [23] developed a concrete Life Cycle Assessment system (CLAS) suitable for the Korean concrete industry and found that ordinary Portland cement contributed the most intensely to global warming potential and photochemical oxidant creation, and aggregates, to acidification, eutrophication, abiotic depletion, and ozone depletion. The authors further discovered that a reduction in all impact categories could be achieved by an increase in the mix ratio of recycled aggregates. Roh, et al. [24] analyzed the embodied environmental impacts of Korean apartment buildings. They found that the tower-type apartment buildings having a flat plate structure recorded the lowest environmental impact for all impact categories, while the wall-structured plate-type apartment buildings had the highest impacts, concluding that the former should be considered during the building design stage if a reduction in potential environmental impacts is to be attained. Moreover, Na and Paik [25] assessed the environmental impacts of the voided slab system in comparison with the ordinary reinforced concrete slab. They discovered that the ordinary reinforced concrete slab had a total greenhouse gas (GHG) emission of 256,599 and 13,989 kg CO_2.eq for concrete and forms respectively, and the voided slab system had a GHG emission of 224,945 and 12,211 kg CO_2.eq; thus, concluding that the voided slab system had a better environmental performance than the ordinary reinforced concrete slab. Furthermore, Paik, et al. [26], in their study, on CO_2 emissions assessment in Korean high-rise commercial residential buildings verified the environmental performance of a developed novel void deck slab (VDS) system in comparison with the ordinary reinforced concrete slab. The result showed a 34% less emission from the void slab system with reference to the ordinary reinforced concrete slab with total CO_2 emissions of 204,433.06 and 151,754.75 kg CO_2.eq, respectively.

With respect to dams and bridges, Noh, et al. [27] analyzed and characterized the life cycle CO_2 emissions for fill dams. They reported that the highest contributor to the total CO_2 emissions of fill dams were materials and that the CO_2 emissions increased with an increase in the use period, concluding that the selection of construction materials and repair methods with low carbon dioxide emissions would reduce total emissions in the life cycle of fill dams. Noh, et al. [28] also characterized CO_2 emissions during the construction process of reservoir embankment elevation. Results indicated that the construction of a water supply process generated the highest emissions among all processes in the two sites studied, with emissions due to equipment and materials generating the most emissions in site A and B respectively. The study thus concluded that CO_2 emissions characteristics differed with varying construction processes, suggesting the optimization of construction processes for the development of environmentally friendly infrastructure.

With respect to road construction, [22] analyzed the characteristics of environmental load occurring during the maintenance and management phase of roads. Results showed a high concentration of terrestrial eco-toxicity and global warming potential with 42.45% and 27.65% respectively, implying that environmental load occurs in major material items of road maintenance and management. On the other hand, Ko, et al. [29] who quantitatively analyzed the environmental impact of the Korean construction industry at large, reported an increase in environmental load by 5.4% annually, with the building construction recording a higher environmental effect than civil constructions.

3.3. Energy-Related LCA Studies

Korea is a high energy-emitting country with a target value of reducing its GHG emissions by up to 37% compared to the business as usual (BAU) levels [7]. This justifies the increasing studies over the years on the environmental impact of energy production and consumption activities in the country, aimed at achieving sustainable development [30].

Due to increasing energy consumption as well as environmental concerns over the years, energy studies geared towards sustainable development considering both economic and environmental protection are highly sort after. In that regard, Lee [31] assessed the environmental impact of Korea's nuclear and coal power generation system, reporting that power generation from the nuclear fuel cycle resulted in lower environmental impacts than from the coal. Moreover, in an effort to assess the holistic impacts on the environment of shipping-related issues, Hwang, et al. [32] comparatively analyzed the environmental impact of using liquefied natural gas (LNG) and conventional marine gas oil (MGO) as marine fuels. Results showed that the LNG cases were significantly lower than the MGO cases in all environmental impact categories involved, thereby suggesting the use of LNG as an effective marine pollutant reducer.

In a similar vein, reports have shown that massive levels of greenhouse gases are being generated from sewer pipeline systems due to high electric energy consumption, necessitating the investigation of the main environmental impacts of wastewater treatment plants. Kyung, et al. [33] estimated the GHG emissions from sewer pipeline system in Daejeon Metropolitan City and discovered that the GHG emissions varied with size and materials of the pipeline. By size, the smaller the pipe diameter, the lower the GHG emissions; and by materials, concrete pipe generated the least GHG emissions. Chang, et al. [34] also analyzed the energy consumption and greenhouse gas emissions from eight fully functional water reuse systems in Korea, reporting that the decentralized reuse systems were more energy-efficient in comparison with the centralized system, thus suggesting the use of the decentralized system as a means of curbing climate change impact.

Other findings related to the construction, energy, as well as the manufacturing, transportation, agriculture, and the information and telecommunications sectors are reported in Table 3. The findings highlight several points regarding LCA research in the aforementioned sectors, with respect to the product and impact categories considered.

Table 3. Summary of South Korea's LCA studies found online.

s/n	Product	Sector	Impact Categories	Important Findings	References
1.	Building	Construction	Various	Building constructions possess life cycle stages of construction, operation and maintenance, and demolition and dismantling; capable of causing significant changes to the environment.	Lee, et al. [35]
2.	Building materials	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	Ordinary Portland cement contributed most intensely to global warming and photochemical oxidant creation, and aggregates, to other categories.	Kim and Tae [23]
3.	Building	Construction	CO_2 emissions	The results of a building life cycle CO_2 assessment using standard apartment houses indicated a figure similar to the existing one for apartment houses.	Tae, et al. [36]
4.	Building	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The primary building materials derived based on weight exhibited significant values with error rates of less than 5%.	Lim, et al. [37]
5.	Building	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The choice of building materials can affect the GHG emissions during the construction phase of a building.	Gong, et al. [38]
6.	Building	Construction	CO_2 emissions	The developed model predicted the environmental performance of construction projects to support low-carbon building designs.	Roh and Tae [39]
7.	Dimethyl ether	Energy	CO_2 emissions and energy consumption	The assessment of coal-based dimethyl ether production system is essential for sustainable dimethyl ether production in Korea.	Kim, et al. [40]
8.	Building	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The integrated building LCA model can predict the contribution of individual building materials to the overall environmental impact of a building.	Lee, et al. [41]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
9.	Bridge	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The equation model generated from this study is meaningful for the prediction of future environmental impacts during the life cycle of bridges.	Kim, et al. [42]
10.	Building materials	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The tower-type apartment buildings with a flat plate structure exhibited the lowest environmental impacts, whereas the plate-type apartment buildings with a wall structure showed the highest environmental impacts.	Roh, Tae and Kim [24]
11.	Waste treatment	Energy	Energy consumption and CO_2, SO_X, and NO_X emissions	A nation-specific LCI value can significantly change the results of an environmental impact assessment.	Oa and Park [43]
12.	Wood pallets and steel cradles	Transportation	Carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutri, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, and mineral extraction	The reusable coil cradle that was reused 20 times had a lower environmental impact than disposable wood dunnage.	Choi, et al. [44] *
13.	Building materials	Construction	Particulate matter (PM), NH_3, NO_X, and SO_2	The amount of PMF emission factor was the most in plate glass.	Kim and Tae [45]
14.	Liquefied Natural Gas (LNG) and Marine Gas Oil (MGO)	Energy	Particulate matter, global warming potential, acidification potential, photochemical potential, and eutrophication potential	The emission levels for the LNG cases are significantly lower than the MGO cases in all potential impact categories.	Hwang, Jeong, Jung, Kim and Zhou [32]
15.	Building materials	Construction	Energy consumption and GHG emissions	Manufacturing building materials contribute most to the total GHG emissions where concrete is responsible for nearly 1/2 of all emissions.	Na and Paik [25]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
16.	Building materials	Construction	Energy consumption and CO_2 emissions	The highest contributor to CO_2 reduction is the embodied carbon dioxide emissions of the building materials.	Paik and Na [46]
17.	Soybean	Agriculture	Energy consumption and GHG emissions	Greenhouse gas emissions are not significantly different between the organic and conventional soybean-farming systems.	Lee and Choe [47]
18.	Building materials	Construction	CO_2 emissions	The total CO_2 emissions of the void slab system were 34% less than that of the ordinary reinforced concrete slab.	Paik, Na and Yoon [26]
19.	Building	Construction	Ozone depletion, global warming, smog, acidification, eutrophication, carcinogens, non-carcinogens respiratory effects, ecotoxicity, and fossil fuel depletion	The environmental impacts of both the roof garden and farm were 2.4–35 times as high as the impacts of the flat roof.	Kim, et al. [48]
20.	Dams	Construction	CO_2 emissions	Materials were the biggest contributor for emissions at all study sites.	Noh, Son and Park [27]
21.	Building	Construction	CO_2 emissions	The proposed Green Building Index Certification System is valid in the promotion of voluntary carbon emission reduction.	Roh, et al. [49]
22.	Rice	Agriculture	Climate change potential, cancerous effects human toxicity potential, non-cancerous effect human toxicity potential, particulate matter potential, photochemical ozone formation potential, acidification potential, terrestrial eutrophication potential, aquatic eutrophication potential, and freshwater aquatic ecotoxicity potential	The rice farming systems with eco-labeling certifications have reduced the environmental impacts.	Kim, et al. [50]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
23.	Industrial waste	Energy	GHG emissions	The GHG benefits from industrial symbiosis exchanges developed through collaborations of giving companies and receiving companies could be effectively distributed by the 50/50 allocation method.	Kim, et al. [51]
24.	Building	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The environmental impacts of each environmental impact category were largely generated at the production and operation stages.	Lim and Tae [52]
25.	Wastewater treatment	Energy	GHG emissions	Pipes with smaller diameter emitted less GHG, and the concrete pipe generated lower amount of GHG than pipes made from other materials.	Kyung, Kim, Yi, Choi and Lee [33]
26.	Vehicles	Manufacturing	GHG emissions	The transportation activities of total finished vehicles made in South Korea generate a significant amount of carbon emissions and a negligible amount of nitrous oxide to the atmosphere.	Sim and Sim [53]
27.	Coating materials	Manufacturing	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	A silver-plating process was identified as a key process driving a substantial fraction of the environmental impact of the product system.	Suh, et al. [54]
28.	Building materials	Construction	CO_2 emissions	Mixing inorganic construction wastes in appropriate proportions with greater than 85 wt % limestone content could be used to develop various types of Portland cement.	Kim, et al. [55]
29.	Building materials	Construction	Energy consumption and CO_2 emissions	The application of high-strength deformed bars is advantageous as a means of carbon dioxide reduction in the studied structural systems.	Cho and Na [56]
30.	Buildings	Construction	CO_2 emissions	The characteristics of life-cycle CO_2 emission reductions and the service life of apartment buildings can be analyzed using green technologies.	Kim, et al. [57]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
31.	Wastewater treatment	Energy	Energy consumption and GHG emissions	Decentralized water reuse is the key to an energy-efficient water management with minimal impact on climate change.	Chang, Lee and Yoon [34]
32.	Buildings	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone layer depletion, photochemical oxidant creation, human carcinogenic potential, human non-carcinogenic potential, and environmental cost	Benchmarks are useful to determine environmental impact reduction of new buildings.	Ji, et al. [58]
33.	Industrial waste	Energy	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	Global Warming Potential and Acidification Potential accounted for 80% and 70% of total environmental impact respectively.	Kim, et al. [59]
34.	Building materials	Construction	CO_2 emissions	Compared to conventional buildings, low-carbon buildings revealed a 25% decrease in carbon emissions in terms of the reduction of Life Cycle CO_2 ($LCCO_2$) per unit area.	
35.	Buildings	Construction	CO_2 emissions	The analyses enabled the development of the Building Simplified Life Cycle CO_2 emissions Assessment Tool.	Roh and Tae [39]
36.	Building materials	Construction	CO_2 emissions	According to building types, CO_2 emission was found to decrease, from highest to lowest, apartment buildings, office buildings, and multipurpose buildings.	Kim, et al. [60]
37.	Buildings	Construction	Global warming potential, acidification potential, eutrophication potential, abiotic depletion, ozone depletion, and photochemical oxidant creation	The steel and concrete have the largest influence on global warming potential, acidification potential, and eutrophication potential.	Sim, et al. [61]

Table 3. *Cont*.

s/n	Product	Sector	Impact Categories	Important Findings	References
38.	Buildings	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The developed model can quantify the embodied environmental impacts of buildings more comprehensively, and can be used as a tool for selecting environment-friendly buildings.	Jang, et al. [62]
39.	Buildings	Construction	CO_2 emissions	The quantities of materials required in the construction and maintenance phases of residential buildings and the developed model can predict assessment of the consequent CO_2 emission.	Moon, et al. [63]
40.	Reservoir embankment	Construction	CO_2 emissions	The construction of a water supply process generated the most emissions among all processes for the study sites.	Noh, Son, Bong and Park [28]
41.	Oil consumption	Energy	Energy consumption and GHG emissions	The amount of "avoided energy" in Israel through the importation of Korean cars is significant.	Yu, et al. [64]
42.	Electroplating, plastic deformation and aluminum foam production	Construction	Acidification, eutrophication, global warming, ozone depletion, photochemical oxidation, and terrestrial ecotoxicity	The alteration of PCB making process by introducing Cu recovery and reuse step resulted in the most appreciable minimization of the overall environmental impact.	HAN [18]
43.	Tilting train	Transportation	Primary Energy, CO_2, and NO_x	Composite scenarios have less impact compared to steel and aluminum options for Respiratory in-organics, Global warming and nonrenewable energy categories.	Blanc, et al. [65]
44.	Railway	Transportation	Global warming, acidification, eutrophication, abiotic depletion, ozone layer depletion, and photochemical oxidant creation	T-car with the car-body of aluminum showed the lowest environmental impact in the use of electric motor unit (EMU) because of its less weight.	Kim, et al. [66]
45.	Municipal solid waste	Energy	Global warming potential, eutrophication, acidification, and ozone depletion	The analysis results indicated that the anaerobic co-digestion of food waste with food waste leachate was a more environmentally preferable method in treating food waste than the feed manufacturing and composting methods.	Padeyanda, et al. [67]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
46.	Electricity	Energy	Abiotic resources depletion potential, global warming potential, ozone depletion potential, acidification potential, aquatic ecotoxicity, and nutrification potential	Power generation by the nuclear fuel cycle causes a lesser environmental impact than coal.	Lee [31]
47.	Municipal solid waste	Energy	Abiotic resource depletion potential, acidification potentials, eutrophication potentials, global warming potential, human toxicity potential, ozone depletion potentials, photochemical oxidant creation potentials, and ecotoxicology potential	Increasing municipal solid waste (MSW) recycle may remove organic compounds from MSW, thus ensuring environmental improvement in each treatment process.	Yoon, et al. [68]
48.	Buildings	Construction	Global warming, acidification, eutrophication, photochemical oxidant creation, and inanimate resource depletion	In terms of apartment buildings constructed in Korea, global warming had the greatest impact on the atmospheric environment.	Cho, et al. [69]
49.	Battery electric vehicles	Transportation	Abiotic depletion potential, acidification potential, eutrophication potential, global warming potential, human toxicity potential, ozone depletion potential, photochemical oxidants creation potential, and particulate matter	The weighted environmental impact of Korea's national power grid supply would increase overall by 66% from 2015 to 2029 using the plan laid out by the 7th Power Roadmap, and by only 33% from 2017 to 2031 using the 8th Power Roadmap plan.	Kim, et al. [70]
50.	Power plant/Oil refinery/Steel plant/Petrochemical plant	Energy	CO_2 emissions	Results showed that the steel and oil refinery industries are relatively environmentally benign because they emit a lower quantity of acidifying substances than do the power and the petrochemical industries.	Lee, et al. [71]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
51.	Bridges	Construction	Abiotic resource depletion, acidification, eutrophication, global warming, ozone depletion, photochemical oxidant creation, terrestrial eco-toxicity, and human toxicity	In terms of the distribution of material-specific environmental load, ready-mixed concrete occupied the highest percentage, followed by rebar, timber, plywood, cement, diesel, rear plate, and other, respectively.	Choi, et al. [72]
52.	Roads	Construction	Abiotic resource depletion, acidification, Eutrophication, global warming, ozone depletion, photochemical oxidant creation, terrestrial eco-toxicity, and human toxicity	A greater percentage of environmental load occurring in the entire pavement repair work was from asphalt concrete material, followed by ready-mixed concrete and lane painting paint respectively.	Im, et al. [73]
53.	Lithium-ion battery electric bus and diesel bus	Transportation	Global warming potential	Energy consumption and emissions of Electric Vehicle bus is better than Diesel Bus.	Jwa and Lim [74]
54.	Municipal solid waste	Energy	Abiotic resource depletion, acidification, eutrophication, global warming, ozone depletion, photochemical oxidant creation, terrestrial eco-toxicity, and human toxicity	Results indicate that the solid refuse fuel plant with bio drying for pellet products was the most preferred option in terms of global and regional impacts followed by the plant with natural air-drying and fluff-type product.	Yi and Jang [75]
55.	Water purifier	Manufacturing	Global warming and abiotic resource depletion	Product operation was the most significant contributor to the selected environmental impacts for both conventional and rental models.	Chun and Lee [76]
56.	Power-plant	Energy	CO_2 emissions	Gas-type plants and SAS sequestration method minimize cost, whereas coal-type plants and DGR sequestration minimize environmental impacts.	Lee, et al. [77]
57.	Building and building materials	Construction	Global warming, acidification, eutrophication, ozone layer depletion, photochemical oxidation, and abiotic depletion potentials	Five major building tasks and six major building materials accounted for more than 95% of the values of six environmental impact categories.	Roh, et al. [78]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
58.	Power-plant	Energy	Abiotic depletion, acidification, eutrophication, freshwater aquatic eco-toxicity, global warming, human toxicity, marine aquatic eco-toxicity, ozone depletion, photochemical ozone creation, and terrestrial ecotoxicity potential	Combined exergoeconomic and exergoenvironmental analyses are useful for finding improvement potentials for system optimization by simultaneously evaluating economic and environmental impacts.	Kim, et al. [79]
59.	Roads	Construction	Administrative district, road height, road division, design speed, and geographical feature	Environmental load of road earthwork zone was affected by the fluctuation of earth-volume such as banking.	Park, et al. [80]
60.	Building materials	Construction	CO_2 emissions	The transportation and manufacture stages had little effect on total CO_2 emissions.	Kim and Chae [81]
61.	Municipal solid waste	Energy	Global warming potential, acidification potential, eutrophication potential, and photochemical oxidant creation potential	The proper disposal of the final residues, such as solid sludge and screened materials, could aid in reducing environmental burdens.	Padeyanda, et al. [82]
62.	Buildings	Construction	CO_2 emissions	The study developed an appropriate building life cycle carbon emissions assessment program, which can support Korea's Green Building Index (GBI) certification system effectively.	Roh, et al. [83]
63.	Building materials	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The study developed the green template to support users in the efficient production of an embodied environmental impact evaluation of a building based on building information modelling (BIM).	Lee, et al. [84]
64.	Medical waste	Energy	Global warming potential, photochemical oxidant creation potential, acidifications potential, and human toxicity	Incineration with heat recovery is the best solution to waste treatment; however, when heat recovery is impossible, incineration without heat recovery is the next best choice.	Koo and Jeong [85]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
65.	Buildings	Construction	Energy consumption and Global warming potential	The study developed a model for assessing energy consumption and GHG emissions at a building's construction phase, observing that the material manufacturing stage had the largest amount of energy consumption and GHG emissions.	Hong, et al. [86]
66.	Building and civil construction	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The study confirmed that building construction was greater than civil construction in terms of the effect on environment.	Ko, Jeon, Cho, An and Choi [29]
67.	Building materials	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The study proposed a simplified environmental impact assessment method based on selection of major building materials for school buildings in Korea.	Roh and Tae [87]
68.	Building materials	Construction	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation	The value of global warming was smaller in passive apartment house in comparison to general apartment house.	Gong, et al. [88]
69.	Silicon-based photovoltaic (PV) systems	Energy	Global warming potential, fossil-fuel consumption, CO_2 payback time, and energy payback time	Single-crystalline silicon and multi-crystalline silicon photovoltaic systems are superior to the current grid mix in Korea with respect to global warming potential and fossil fuel consumption.	Kim, et al. [89]
70.	New and renewable energy	Energy	CO_2 emissions	The economic and environmental effects of using new and renewable energy (NRE) for selecting the optimum NRE system in educational facilities were assessed.	Hong, et al. [90]
71.	Coal, natural gas, nuclear power, hydro power, geothermal power, wind power, solar thermal power, and solar photovoltaic (PV) power	Energy	GHG emissions	Coal and wind power locate the highest and the lowest life cycle GHG emissions.	Kim, et al. [91]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
72.	Fuel	Energy	Energy consumption and GHG emissions	A new environmental targeting procedure was developed that provides a consistent, general procedure for determining the mass flowrates and the efficiencies of used turbines.	Manesh, et al. [92]
73.	Vehicles	Manufacturing	Abiotic depletion, acidification, eutrophication, freshwater aquatic eco-toxicity, global warming, human toxicity, marine aquatic eco-toxicity, ozone depletion, photochemical ozone creation, and terrestrial ecotoxicity potential	Environmental assessment system of vehicle is developed by GM Korea Company to help manage the problem of vehicle LCA analysis based on automated and standardized data management and processing methods.	Yu and Kim [93]
74.	Carbon capture and storage (CCS) infrastructure	Energy	GHG emissions	The CO_2 capture in coal-fired power plants is more preferred than in the gas-fired power plant since the coal−MEA capture facility is a more eco-friendly solution.	Lee, et al. [94]
75.	Steel	Construction	GHG emissions	The structural system choice has a significant impact on the total amount of materials used and $LCCO_2$ and other GHG emissions.	Cho, et al. [95]
76.	Building materials	Construction	CO_2 emissions	The life-cycle CO_2 emission from concrete increased linearly as the compressive strength of the concrete increased.	Park, et al. [96]
77.	Hydrogen fuel cell buses	Manufacturing	Global warming potential, fossil-fuel consumption, and regulated air pollutants	The study concluded that H_2 pathways are more competitive than conventional fuels from an eco-efficiency perspective.	Lee, et al. [97]
78.	Wind-hydrogen system	Transportation	Global warming potential, fossil-fuel consumption, regulated air pollutants, and abiotic resource depletion	The WE [Wind] exhibited lower abiotic resource depletion rate, global warming potential and much smaller regulated air pollutants in comparison with gasoline.	Lee, et al. [98]
79.	Hydrogen	Energy	Global warming potential, fossil-fuel consumption, and regulated air pollutants	Water Electrolysis with wind power is superior regarding global warming potential, fossil fuel consumption and regulated air emissions.	Lee, et al. [99]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
80.	Domestic waste	Energy	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, photochemical oxidant creation, eco-toxicity, and human toxicity	The evaluation of the environmental score of materials recovered from waste home appliances to calculate their recycling potential showed that recycled glass and circuit board had the highest value of environmental score, followed by steel, copper and aluminum, and plastic.	Kim, et al. [100]
81.	Tilting train	Transportation	Energy consumption and GHG emissions	The use phase of the car-body has the largest environmental impact for all scenarios, with near negligible contributions from the other phases.	Castella, et al. [101]
82.	Rail track systems	Transportation	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, photochemical oxidant creation, eco-toxicity, and human toxicity	The study analyzed the environmental performance of ballast and concrete track systems, showing that the former had a better environmental position.	Lee, et al. [102]
83.	Food waste	Energy	Global warming, human toxicity, freshwater aquatic ecotoxicity, acidification, and eutrophication	Acidification, eutrophication, and freshwater aquatic ecotoxicity impact increased due to the increase of food waste recycling.	Lee, et al. [103]
84.	Vehicles	Manufacturing	Abiotic resource depletion, global warming, ozone depletion, photochemical oxidant creation, eutrophication, and human toxicity	The recycling processes of ferrous metals appear to have the most significant environmental impacts in the End-of-Life Vehicle treatment system.	Jeong, et al. [104]
85.	Personal computer	Telecommunication	Abiotic depletion, global warming, ecotoxicity, human toxicity, acidification, ozone layer depletion, photo-oxidant formation, and eutrophication	The PC recycling should be raised up to at least 63% in order to reduce the environmental burdens of a PC in other life cycle stages (pre-manufacturing, manufacturing, usage, and disposal stages).	Choi, et al. [105]
86.	Urban water infrastructure	Manufacturing	Resource depletion, global warming, acidification, ozone layer depletion, photochemical ozone creation, and eutrophication	A mathematical model was developed whose integration and optimization decreased average concentrations of influents supplied for drinking water, total consumption of water resources and electricity, life cycle costing, and water resource dependency.	Lim, et al. [106]

Table 3. *Cont.*

s/n	Product	Sector	Impact Categories	Important Findings	References
87.	Petrochemical products	Energy	Resource depletion, global warming, stratospheric ozone depletion, acidification, eutrophication, photo-oxidant formation, human toxicity, and ecological toxicity	The environmental performance associated with polystyrene production could be improved through the reduction of the amount of the raw materials required.	Hur, et al. [107]
88.	Nuclear power	Energy	Abiotic resources depletion potential, global warming potential, ozone depletion potential, acidification potential, aquatic and terrestrial ecotoxicity, and nutrification potential	The important environmental impacts caused by nuclear power generation system are the abiotic depletion, human toxicity and global warming.	Lee, et al. [108]
89.	Electronics	Manufacturing	Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, photochemical oxidant creation, eco-toxicity, and human toxicity	By comparing the hybrid and process LCA in the cradle-to-gate stage, the gap between both methods of the 42-in. standard definition plasma display panel (PDP) ranges from 1% (acidification impact category) to −282% (abiotic resource depletion impact category), with an average gap of 68.63%. The gaps of the impact categories of acidification (AP), eutrophication (EP), and global warming (GWP) are relatively low (less than 10%).	Eun, et al. [109]
90.	Electronics	Manufacturing	Several	The gap between Samsung Techwin and the leading companies in terms of development of environment-friendly products was 60%, thus components and processes needed for improvements were located.	Kang, et al. [110]
91.	Tractors	Manufacturing	GHG emission, acidification, ozone depletion, photo-oxidant creation, eutrophication, and summer and winter smog	Based on the impact assessment results, most environmental impacts occurred at the use stage owing to the emissions from diesel engine operation.	Lee, et al. [111]

* Available online before 2020.

4. Discussion

Through active participation in international conferences and collaborations with other countries, Korea has progressively developed its domestic methodological approaches and databases for LCA analysis since the mid-1990s. Conscious efforts at integrating environmental impact results into processes of decision-making in industries has been a major reason for the increasing trend of LCA studies in the country. The Korean Ministry of Environment [112] mainly controls activities in relation to environmental sustainability assessments. They do this in conjunction with the Korea Environmental Industry and Technology Institute (KEITI), Korea Environment Institute (KEI), Korea Institute of Industrial Technology (KITECH), Korea National Cleaner Production Center (KNCPC), Korea Environmental Preservation Association (KEPA), Korean Society for Life Cycle Assessment (KSLCA), and a host of other organizations. These units work together towards advanced technology development for the environmental industry and public policy, by providing open access to their database of LCA and other relevant environmental information collected since the mid-1990s (KEITI 2020). The domestic database of Life Cycle Inventory (LCI) has developed over time since its inception in 1998, even though the current state of data has been reported not to meet industrial demand [113].

Though a majority of the LCA studies (as observed) were reported for the construction and energy sectors, more results were expected especially for the other sectors (agriculture, manufacturing, transportation, and information and communication). This is because they are also key players of the economy and major GHG emitters. For instance, since the automotive industry is one of the largest industries of the manufacturing sector of Korea, it consumes large amounts of energy, producing correspondingly large amounts of carbon emissions in its entire supply chain [53]. In addition, the rapidly expanding middle-class population of Korea has led to an unavoidable increase in car ownership, raising concerns on the resulting climatic implications of the transportation sector [70]. These situations call for the need to improve and further increase research in not only the construction and energy sectors, but all major economic sectors as well.

Furthermore, the incorporation of LCA into circular economy (CE) strategies for all economic sectors has been a topic of discussion in South Korea in recent times in response to the merger of Act on resources saving and recycling promotion of 1992 and the recent framework on resource circulation to promote the purchase of green products (Figure 6). CE as a relatively new model, promotes the maximum reuse/recycling of materials and products in order to reduce to the largest possible extent, the waste generation [114]. South Korea is a heavy importer of critical raw materials essential for its main industries, such as the automobile industry [115], and is also currently in a transition state from fossil fuels and nuclear power to renewable energy sources [116]. In all of these processes, waste has become a valuable resource and thus the country is moving towards a sustainable resource-circulating society [117]. This is evident by the enactment of extensive waste legislations such as the Construction Waste Recycling Promotion Act (2005), Act on Resource Circulation of Electrical, Electronic Equipment and Vehicles (2008), Act on Waste Treatment Facilities Promotion and Support Surrounding Area (1995), and Act on Transboundary Movement and Treatment of Waste (1992) [116] (Figure 6).

Despite these legislations, we discovered that the majority of the reviewed studies did not take into account the economic and social aspects for a complete sustainability assessment [118]. Thus, adopting the LCA approach together with the CE principle would be the way forward to achieving a comprehensive assessment since environment, social, economic, business, and policy aspects are already integrated with the CE framework [119]. In other words, the LCA complements the CE by assessing environmental impacts, whilst the CE provides a strategic framework for closed-loop material flows; thus providing critical evidence for effective policy and decision-making.

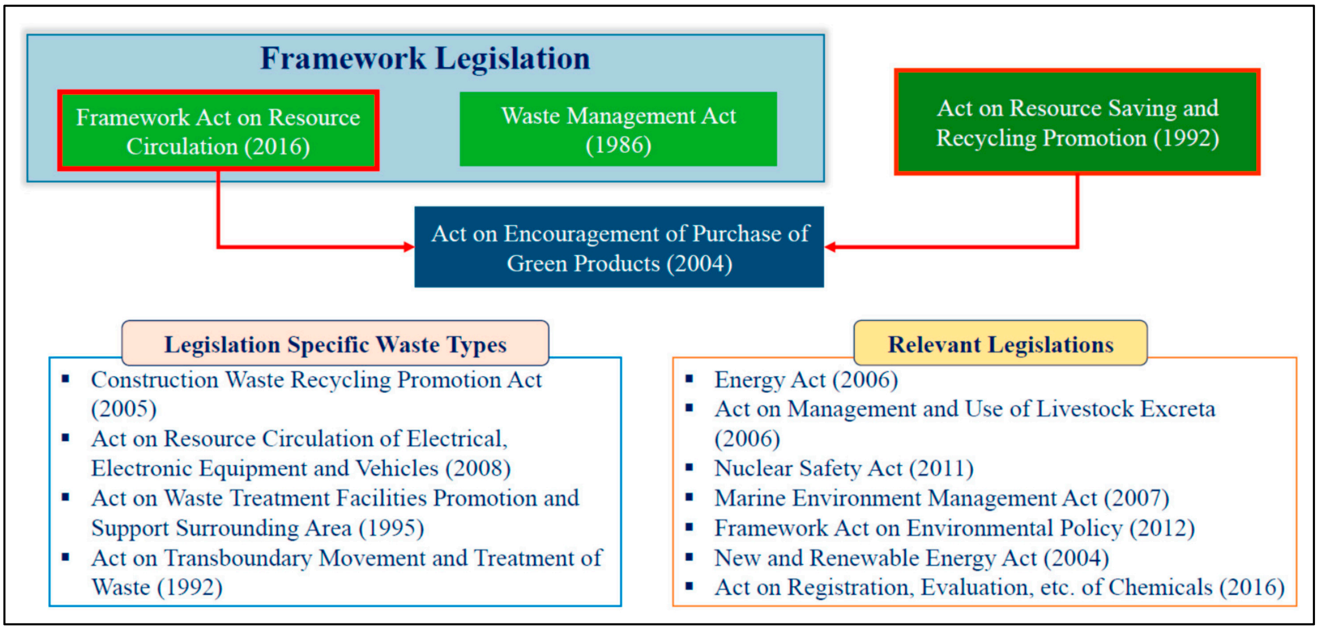

Figure 6. South Korea's Circular Economy Legislation [116].

4.1. Implications of the GRI Reports

The importance of sustainability reporting cannot be overemphasized. This is because it helps in the management of environmental, social, and economic impacts of organizations, as it relates to their operations within a country. The GRI reports showed an active environmental consciousness and reporting system in South Korea, even though these data might not be based on the LCA principles. Results showed more focus on financial services and construction industries. However, overall reports showed that contributions to the GRI database came from a number of diverse industries within the country. Even though the GRI reports were fewer in number than the LCA's, the search here only included a single year (2017). Hence, there were more single-year studies compared to the LCA results, indicating the potential to expand some of these GRI reports into full LCA studies [14].

4.2. Areas of LCA Research Focus

This section suggests some potential research areas needing LCA analysis, based on their growing importance to the Korean economy.

4.2.1. Tourism

Records of tourism activities all over the world indicate the significant growth rate of the tourism sector, making it an important industry in world economies. In Korea specifically, the tourism sector has been on the rise, contributing significantly to the GDP of the country (Figure 1b). This growing role requires the thorough assessment of tourist services in the country, from an environmental point of view. In other words, it is necessary to carryout accurate environmental impact assessments of tourist products. Throughout the search procedure adopted, no study was found for the tourism sector of Korea. This is possibly due to the general lack of specific LCA databases for tourism or the low consideration of environmental-impact categories of the tourism industry [120]. There have been calls in recent years for the sustainable development of the tourism sector [121]. Hence, we recommend some improvements to the tourism sector, taking into account the environmental implications of tourism activities in Korea, while also considering the economic impacts.

4.2.2. Agriculture

Korea's agriculture sector requires an improvement in LCA studies as well. Attention should be paid to the environmental assessment of important agricultural products, such as pork, beef, milk, potatoes, barley, and vegetables, all of which make up a huge proportion of the GDP contribution of the sector. There are also calls for further research on the environmental performance of smallholder farms in Korea. This is because recent studies have discovered a surprisingly large amount of GHG emissions and low energy efficiencies (EEs) in small unit farms when compared with large-scale farms [47].

4.2.3. Health

The health industry is another sector lacking in LCA studies in Korea. This sector contributes significantly to climate change through its energy emission (heating, ventilation, lighting, and hot-water generation), transportation (staff, patients, and visitors), and supply-chain activities involved in producing healthcare-related products. It is therefore imperative that climate-friendly measures be introduced to curb the direct and indirect negative health sector impacts [122]. For a nation with an advanced healthcare system, it is recommended that environmental assessments be undertaken on a regular basis, in the course of meeting the growing demand for healthcare resources.

5. Conclusions

This study sought to assess the status of life-cycle assessment studies pertaining to South Korea. Through a bibliometric review of available studies, the paper quantitatively characterized Korea-related LCA research from 2000 to 2019. The LCA is a rapidly developing technique of quantitative environmental assessment in South Korea, with an increasing number of reports published especially in English language over the years, as observed from the study. A total of 91 English-written LCA articles were discovered for South Korea. The majority of these reports focused on the construction and energy industries, with fewer reports found for the manufacturing, transportation, agriculture, and information and communication industries. Korea as a major world GHG emitter has been a major campaigner for environmental sustainability research, explaining the increasing number of studies over time in the areas of LCA, carbon, water, and ecological footprints. However, as it concerns LCA, this study has shown that research gaps exist in some relevant sectors of the economy, thus recommending the improvement and expansion of research. While there is a possibility of missing some studies due to language or search restrictions applied, the study has revealed, through the GRI report, that there exists a large number of environmental sustainability reports in the country, and gives an insight into the areas of concentration as far as Korean LCA studies are concerned.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13116234/s1, Table S1: Summary of South Korea's water footprint studies found online (2000–2019). Table S2: Summary of South Korea's carbon footprint studies found online (2000–2019).

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References

1. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef]
2. Karkour, S.; Ichisugi, Y.; Abeynayaka, A.; Itsubo, N.J.S. External-cost estimation of electricity generation in G20 countries: Case study using a global life-cycle impact-assessment method. *Sustainability* **2020**, *12*, 2002. [CrossRef]
3. IMF. World Economic Outlook: World Economic and Financial Surveys. Available online: https://www.imf.org/external/pubs/ft/weo/2019/02/weodata/index.aspx (accessed on 31 August 2020).
4. WITS. Korea, Rep. Trade Statistics: Exports, Imports, Products, Tariffs, GDP and Related Development Indicator. Available online: https://wits.worldbank.org/CountryProfile/en/KOR (accessed on 11 September 2020).
5. Nordeatrade. The Economic Context of South Korea. Available online: https://www.nordeatrade.com/fi/explore-new-market/south-korea/ (accessed on 11 September 2020).
6. KEEI. Monthly Energy Statistic, Page 67. Available online: http://www.keei.re.kr/keei/download/MES1803.pdf (accessed on 11 September 2020).
7. Adelodun, B.; Choi, K.S. Impact of food wastage on water resources and GHG emissions in Korea: A trend-based prediction modeling study. *J. Clean. Prod.* **2020**, *271*, 122562. [CrossRef]
8. IEA. CO_2 Emissions from Fuel Combustion. Available online: http://energyatlas.iea.org/#!/tellmap/1378539487 (accessed on 11 September 2020).
9. Kim, H.C.; Kim, S.; Kim, B.-U.; Jin, C.-S.; Hong, S.; Park, R.; Son, S.-W.; Bae, C.; Bae, M.; Song, C.-K. Recent increase of surface particulate matter concentrations in the Seoul Metropolitan Area, Korea. *Sci. Rep.* **2017**, *7*, 4710. [CrossRef]
10. OECD. Available online: https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm (accessed on 31 March 2021).
11. Engelbrecht, S.; Ladenika, A.; MacGregor, O.; Maepa, M.; Bodunrin, M.O.; Burman, N.W.; Croft, J.; Goga, T.; Harding, K.G. A discussion on the availability of life-cycle assessment studies in New Zealand. *Int. J. Life Cycle Assess.* **2018**, *23*, 1708–1713. [CrossRef]
12. Croft, J.; Engelbrecht, S.; Ladenika, A.; MacGregor, O.; Maepa, M.; Bodunrin, M.O.; Burman, N.W.; Goga, T.; Harding, K.G. The availability of life-cycle studies in Sweden. *Int. J. Life Cycle Assess.* **2019**, *24*, 6–11. [CrossRef]
13. Ladenika, A.; Bodunrin, M.O.; Burman, N.W.; Croft, J.; Engelbrecht, S.; Goga, T.; MacGregor, O.; Maepa, M.; Harding, K.G. Assessing the availability of life cycle assessments in Austria. *Int. J. Life Cycle Assess.* **2019**, *24*, 614–619. [CrossRef]
14. Burman, N.W.; Croft, J.; Engelbrecht, S.; Ladenika, A.; MacGregor, O.; Maepa, M.; Bodunrin, M.O.; Harding, K.G. life-cycle assessment, water footprinting, and carbon footprinting in Portugal. *Int. J. Life Cycle Assess.* **2018**, *23*, 1693–1700. [CrossRef]
15. Bodunrin, M.O.; Burman, N.W.; Croft, J.; Engelbrecht, S.; Goga, T.; Ladenika, A.; MacGregor, O.; Maepa, M.; Harding, K.G. The availability of life-cycle assessment, water footprinting, and carbon footprinting studies in Brazil. *Int. J. Life Cycle Assess.* **2018**, *23*, 1701–1707. [CrossRef]
16. Maepa, M.; Bodunrin, M.O.; Burman, N.W.; Croft, J.; Engelbrecht, S.; Ladenika, A.; MacGregor, O.; Harding, K.G. life cycle assessments in Nigeria, Ghana, and Ivory Coast. *Int. J. Life Cycle Assess.* **2017**, *22*, 1159–1164. [CrossRef]
17. Karkour, S.; Rachid, S.; Maaoui, M.; Lin, C.-C.; Itsubo, N. Status of Life Cycle Assessment (LCA) in Africa. *Environments* **2021**, *8*, 10. [CrossRef]
18. HAN, M.-K. The status of LCA for materials processing in Korea. *J. Adv. Sci.* **2002**, *13*, 214–217. [CrossRef]
19. Fortune. Global 500. Available online: https://fortune.com/global500/ (accessed on 20 February 2021).
20. GRI. Sustainability Disclosure Database. Available online: https://database.globalreporting.org/search/ (accessed on 20 February 2021).
21. KOSTAT. GDP by Industry at Current Prices. Available online: https://kostat.go.kr/portal/eng/resources/ (accessed on 6 January 2021).
22. Im, J.; Kim, D.; Liu, J.; Park, J.; Kim, B. Analysis of Construction-specific Environmental Load Characteristics in the Road Paving Work Maintenance & Management Phase. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Kuala Lumpur, Malaysia, 16–18 January 2018; p. 012033.
23. Kim, T.H.; Tae, S.H. Proposal of environmental impact assessment method for concrete in South Korea: An application in LCA (Life Cycle Assessment). *Environ. Res. Public Health* **2016**, *13*, 1074. [CrossRef] [PubMed]
24. Roh, S.; Tae, S.; Kim, R. Analysis of embodied environmental impacts of Korean apartment buildings considering major building materials. *Sustainability* **2018**, *10*, 1693. [CrossRef]
25. Na, S.; Paik, I. Reducing Greenhouse Gas Emissions and Costs with the Alternative Structural System for Slab: A Comparative Analysis of South Korea Cases. *Sustainability* **2019**, *11*, 5238. [CrossRef]
26. Paik, I.; Na, S.; Yoon, S. Assessment of CO_2 Emissions by Replacing an Ordinary Reinforced Concrete Slab with the Void Slab System in a High-Rise Commercial Residential Complex Building in South Korea. *Sustainability* **2019**, *11*, 82. [CrossRef]
27. Noh, S.; Son, Y.; Park, J. Life cycle carbon dioxide emissions for fill dams. *J. Clean. Prod.* **2018**, *201*, 820–829. [CrossRef]
28. Noh, S.; Son, Y.; Bong, T.; Park, J. Characterization of CO_2 emissions during construction of reservoir embankment elevation in South Korea. *Int. J. Life Cycle Assess.* **2014**, *19*, 42–51. [CrossRef]
29. Ko, M.-J.; Jeon, H.-C.; Cho, K.-H.; An, J.-H.; Choi, D.-S. A Trend analysis on the Environmental Impact of Construction Industry in Korea. *Int. J. Appl. Eng. Res.* **2014**, *9*, 24827–24835.

30. Adelodun, B.; Kim, S.H.; Odey, G.; Choi, K.-S. Assessment of environmental and economic aspects of household food waste using a new Environmental-Economic Footprint (EN-EC) index: A case study of Daegu, South Korea. *Sci. Total Environ.* **2021**, *776*, 145928. [CrossRef]
31. Lee, Y.E. Life cycle assessment (Lca) of the power generation system for the establishment of environmental management system in Korea. *Key Eng. Mater.* **2015**, *277–279*, 667–673.
32. Hwang, S.; Jeong, B.; Jung, K.; Kim, M.; Zhou, P. Life cycle assessment of LNG fueled vessel in domestic services. *J. Mar. Sci* **2019**, *7*, 359. [CrossRef]
33. Kyung, D.; Kim, D.; Yi, S.; Choi, W.; Lee, W. Estimation of greenhouse gas emissions from sewer pipeline system. *Int. J. Life Cycle Assess.* **2017**, *22*, 1901–1911. [CrossRef]
34. Chang, J.; Lee, W.; Yoon, S. Energy consumptions and associated greenhouse gas emissions in operation phases of urban water reuse systems in Korea. *J. Clean. Prod.* **2017**, *141*, 728–736. [CrossRef]
35. Lee, K.; Tae, S.; Shin, S. Development of a life cycle assessment program for building (SUSB-LCA) in South Korea. *Renew. Sust. Energ. Rev.* **2009**, *13*, 1994–2002. [CrossRef]
36. Tae, S.; Shin, S.; Woo, J.; Roh, S. The development of apartment house life cycle CO_2 simple assessment system using standard apartment houses of South Korea. *Renew. Sustain. Energ. Rev.* **2011**, *15*, 1454–1467. [CrossRef]
37. Lim, H.; Tae, S.; Roh, S. Analysis of the Primary Building Materials in Support of G-SEED Life Cycle Assessment in South Korea. *Sustainability* **2018**, *10*, 2820. [CrossRef]
38. Gong, Y.; Tae, S.; Suk, S.; Chae, C.; Ford, G.; Smith, M.E.; Steffen, R. Life cycle assessment applied to green building certification in South Korea. *Procedia Eng.* **2015**, *118*, 1309–1313. [CrossRef]
39. Roh, S.; Tae, S. Building simplified life cycle CO_2 emissions assessment tool (B-SCAT) to support low-carbon building design in South Korea. *Sustainability* **2016**, *8*, 567. [CrossRef]
40. Kim, S.; Kim, J.; Yoon, E.S. Evaluation of coal-based dimethyl ether production system using life cycle assessment in South Korea. In *Computer Aided Chemical Engineering*; Elsevier: Amsterdam, The Netherlands, 2012; Volume 31, pp. 1387–1391.
41. Lee, N.; Tae, S.; Gong, Y.; Roh, S. Integrated building life-cycle assessment model to support South Korea's green building certification system (G-SEED). *Renew. Sustain. Energy Rev.* **2017**, *76*, 43–50. [CrossRef]
42. Kim, H.; Tae, S.; Ahn, Y. A study on the environmental impact prediction method of bridge life cycle maintenance using bridge maintenance database. *Int. J. Sustain. Build. Technol. Urban Dev.* **2019**, *10*, 194–204.
43. Oa, S.; Park, J.-W. An Environmental Impact Assessment Model with Monetary Valuation for Remediation in South Korea. *KSCE J. Civ. Eng.* **2019**, *23*, 4168–4173. [CrossRef]
44. Choi, B.; Yoo, S.; Lee, K.-D.; Park, S.-i. An environmental impact comparison of disposable wood pallets and reusable steel cradles: A case study on rolled steel coils in container shipping in South Korea. *Int. J. Sustain. Transp.* **2020**, *14*, 335–342. [CrossRef]
45. Kim, R.; Tae, S. Calculation of particulate matter formation of major building material in construction phase through life cycle impact assessment. *Int. J. Sustain. Build. Technol. Urban Dev.* **2019**, *10*, 65–72.
46. Paik, I.; Na, S. Comparison of Carbon Dioxide Emissions of the Ordinary Reinforced Concrete Slab and the Voided Slab System During the Construction Phase: A Case Study of a Residential Building in South Korea. *Sustainability* **2019**, *11*, 3571. [CrossRef]
47. Lee, K.S.; Choe, Y.C. Environmental performance of organic farming: Evidence from Korean small-holder soybean production. *J. Clean. Prod.* **2019**, *211*, 742–748. [CrossRef]
48. Kim, E.; Jung, J.; Hapsari, G.; Kang, S.; Kim, K.; Yoon, S.; Lee, M.; Han, M.; Choi, Y.; Choe, J.K. Economic and environmental sustainability and public perceptions of rooftop farm versus extensive garden. *Build. Environ.* **2018**, *146*, 206–215. [CrossRef]
49. Roh, S.; Tae, S.; Kim, R. Developing a Green Building Index (GBI) certification system to effectively reduce carbon emissions in South Korea's building industry. *Sustainability* **2018**, *10*, 1872. [CrossRef]
50. Kim, S.; Kim, T.; Smith, T.M.; Suh, K. Environmental implications of eco-labeling for rice farming systems. *Sustainability* **2018**, *10*, 1050. [CrossRef]
51. Kim, H.W.; Ohnishi, S.; Fujii, M.; Fujita, T.; Park, H.S. Evaluation and allocation of greenhouse gas reductions in industrial symbiosis. *J. Ind. Ecol.* **2018**, *22*, 275–287. [CrossRef]
52. Lim, H.; Tae, S. Analysis of the environmental impact emissions for the office building based on analysis of major building materials of life cycle assessment of G-SEED. *Int. J. Sustain. Build. Technol. Urban Dev.* **2018**, *9*, 275–287.
53. Sim, J.; Sim, J. Air emission and environmental impact assessment of Korean automotive logistics. *J. Clean. Prod.* **2017**, *159*, 130–140. [CrossRef]
54. Suh, S.; Lee, K.M.; Ha, S. Eco-efficiency for pollution prevention in small to medium-sized enterprises: A case from South Korea. *J. Ind. Ecol.* **2005**, *9*, 223–240. [CrossRef]
55. Kim, J.; Tae, S.; Kim, R. Theoretical study on the production of environment-friendly recycled cement using inorganic construction wastes as secondary materials in South Korea. *Sustainability* **2018**, *10*, 4449. [CrossRef]
56. Cho, S.; Na, S. The reduction of CO_2 emissions by application of high-strength reinforcing bars to three different structural systems in South Korea. *Sustainability* **2017**, *9*, 1652.
57. Kim, R.; Tae, S.; Roh, S. Development of low carbon durability design for green apartment buildings in South Korea. *Renew. Sustain. Energy Rev.* **2017**, *77*, 263–272. [CrossRef]
58. Ji, C.; Hong, T.; Jeong, J.; Kim, J.; Lee, M.; Jeong, K. Establishing environmental benchmarks to determine the environmental performance of elementary school buildings using LCA. *Energy Build.* **2016**, *127*, 818–829. [CrossRef]

59. Kim, T.H.; Tae, S.H.; Chae, C.U.; Choi, W.Y. The environmental impact and cost analysis of concrete mixing blast furnace slag containing titanium gypsum and sludge in South Korea. *Sustainability* **2016**, *8*, 502. [CrossRef]
60. Kim, T.H.; Chae, C.U.; Kim, G.H.; Jang, H.J. Analysis of CO_2 emission characteristics of concrete used at construction sites. *Sustainability* **2016**, *8*, 348. [CrossRef]
61. Sim, J.; Sim, J.; Park, C. The air emission assessment of a South Korean apartment building's life cycle, along with environmental impact. *Energy Build.* **2016**, *95*, 104–115. [CrossRef]
62. Jang, M.; Hong, T.; Ji, C. Hybrid LCA model for assessing the embodied environmental impacts of buildings in South Korea. *Environ. Impact Assess. Rev.* **2015**, *50*, 143–155. [CrossRef]
63. Moon, H.; Hyun, C.; Hong, T. Prediction model of CO_2 emission for residential buildings in South Korea. *J. Manag. Eng.* **2014**, *30*, 04014001. [CrossRef]
64. Yu, H.; Pearlmutter, D.; Schwartz, M. Life cycle assessment of an energy-economy nexus: The case of Israel and South Korea. *Environ. Impact Assess. Rev.* **2018**, *69*, 61–69. [CrossRef]
65. Blanc, I.; Schwab-Castella, P.; Gomez-Ferrer, M.; Jolliet, O.; Ecabert, B.; Wakeman, M.; Manson, J.-A.; Emery, D. Towards the Eco-design of a tilting train in Korea: Applying LCA to design alternatives. In Proceedings of the 2nd International Congress with Innovation Fair, Sustainable management in action, SMIA 05, Genève, Switzerland, 19–20 September 2005.
66. Kim, Y.-K.; Lee, J.-Y.; Mok, J.K.; Yoon, H.T. Investigations for Life Cycle Assessment (LCA) of Electric Motor Unit (EMU) in Korea. In Proceedings of the 7th World Congress on Railway Research (WCRR), Montreal, QC, Canada, 4–8 June 2006.
67. Padeyanda, Y.S.; Jang, Y.-C.; Ko, Y.; Jeong, G.H. A comparative LCA study of current and future management scenarios of food waste in daejeon metropolitan city in Korea. In Proceedings of the 25rd Annual Conference of Japan Society of Material Cycles and Waste Management, Hiroshima, Japan, 15–17 September 2014; p. 549.
68. Yoon, S.H.; Jung, Y.L.; Lee, D.H.; Choi, D.H.; Yoon, J.H. The Study on the Environmental Load Change of Waste Treatment by Comprehensive National Waste Management Plan Execution with LCA in Korea. In Proceedings of the 17th Annual Conference of The Japan Society of Waste Management Experts, Kitakyushu, Japan, 20 October 2006; p. 409.
69. Cho, K.-H.; Jeon, H.-C.; Baik, Y.-K.; Jung, Y.-H.; Kim, S.-Y. P-40 A Study on the Environmental Impact Evaluation In the Apartment Complexes in Korea Using LCA Method. In Proceedings of the 38th Symposium on Human-Environment System, Nagasaki, Japan, 6–7 December 2014; Volume 38, pp. 225–228.
70. Kim, S.; Pelton, R.E.; Smith, T.M.; Lee, J.; Jeon, J.; Suh, K. Environmental Implications of the National Power Roadmap with Policy Directives for Battery Electric Vehicles (BEVs). *Sustainability* **2019**, *11*, 6657. [CrossRef]
71. Lee, S.-Y.; Lee, I.-B.; Han, J. Design under uncertainty of carbon capture, utilization and storage infrastructure considering profit, environmental impact, and risk preference. *Appl. Energy* **2019**, *238*, 34–44. [CrossRef]
72. Choi, G.; Kim, J.; Sackey, S.; Kim, B. The Environmental Load Characteristic Analysis of LCA-based IPC Girder Bridge. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Banda Aceh, Indonesia, 26–27 September 2018; Volume 164, p. 012032.
73. Heitz, A.; Dablanc, L.; Olsson, J.; Sanchez-Diaz, I.; Woxenius, J. Spatial patterns of logistics facilities in Gothenburg, Sweden. *J. Transp. Geogr.* **2020**, *88*, 102191. [CrossRef]
74. Jwa, K.; Lim, O. Comparative life cycle assessment of lithium-ion battery electric bus and Diesel bus from well to wheel. *Energy Procedia* **2018**, *145*, 223–227. [CrossRef]
75. Yi, S.; Jang, Y.-C. Life cycle assessment of solid refuse fuel production from MSW in Korea. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 19–42. [CrossRef]
76. Chun, Y.-Y.; Lee, K.-M. Environmental impacts of the rental business model compared to the conventional business model: A Korean case of water purifier for home use. *Int. J. Life Cycle Assess.* **2017**, *22*, 1096–1108. [CrossRef]
77. Lee, S.-Y.; Lee, J.-U.; Lee, I.-B.; Han, J. Design under uncertainty of carbon capture and storage infrastructure considering cost, environmental impact, and preference on risk. *Appl. Energy* **2017**, *189*, 725–738. [CrossRef]
78. Roh, S.; Tae, S.; Suk, S.J.; Ford, G. Evaluating the embodied environmental impacts of major building tasks and materials of apartment buildings in Korea. *Renew. Sustain. Energy Rev.* **2017**, *73*, 135–144. [CrossRef]
79. Kim, M.; Kim, D.; Esfahani, I.J.; Lee, S.; Kim, M.; Yoo, C. Performance assessment and system optimization of a combined cycle power plant (CCPP) based on exergoeconomic and exergoenvironmental analyses. *Korean J. Chem. Eng.* **2017**, *34*, 6–19. [CrossRef]
80. Park, J.-Y.; Lee, D.-E.; Kim, B.-S. A study on analysis of the environmental load impact factors in the planning stage for highway project. *KSCE J. Civ. Eng.* **2016**, *20*, 2162–2169. [CrossRef]
81. Kim, T.; Chae, C.U. Evaluation analysis of the CO_2 emission and absorption life cycle for precast concrete in Korea. *Sustainability* **2016**, *8*, 663. [CrossRef]
82. Padeyanda, Y.; Jang, Y.-C.; Ko, Y.; Yi, S. Evaluation of environmental impacts of food waste management by material flow analysis (MFA) and life cycle assessment (LCA). *J. Mater. Cycles Waste Manag.* **2016**, *18*, 493–508. [CrossRef]
83. Roh, S.; Tae, S.; Suk, S.J.; Ford, G.; Shin, S. Development of a building life cycle carbon emissions assessment program (BEGAS 2.0) for Korea's green building index certification system. *Renew. Sustain. Energy Rev.* **2016**, *53*, 954–965. [CrossRef]
84. Lee, S.; Tae, S.; Roh, S.; Kim, T. Green template for life cycle assessment of buildings based on building information modeling: Focus on embodied environmental impact. *Sustainability* **2015**, *7*, 16498–16512. [CrossRef]
85. Koo, J.-K.; Jeong, S.-I. Sustainability and shared smart and mutual–green growth (SSaM-GG) in Korean medical waste management. *Waste Manag. Res.* **2015**, *33*, 410–418. [CrossRef] [PubMed]

86. Hong, T.; Ji, C.; Jang, M.; Park, H. Assessment model for energy consumption and greenhouse gas emissions during building construction. *J. Manag. Eng.* **2014**, *30*, 226–235. [CrossRef]
87. Roh, S.J.; Tae, S.H. Proposal of a Simplified Environmental Assessment Method Based on Major Building Materials for School Buildings in Korea. *Adv. Mater. Res.* **2014**, *905*, 353–356. [CrossRef]
88. Gong, Y.R.; Tae, S.H.; Song, S.W.; Roh, S.J. Environment-friendly Assessment of Passive Apartment House based on Major Building Materials in Korea. *Adv. Mater. Res.* **2014**, *905*, 199–202. [CrossRef]
89. Kim, B.-J.; Lee, J.-Y.; Kim, K.-H.; Hur, T. Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea. *Sol. Energy* **2014**, *99*, 100–114. [CrossRef]
90. Hong, T.; Koo, C.; Kwak, T.; Park, H.S. An economic and environmental assessment for selecting the optimum new renewable energy system for educational facility. *Renew. Sustain. Energy Rev.* **2014**, *29*, 286–300. [CrossRef]
91. Kim, H.; Tenreiro, C.; Ahn, T.K. 2D representation of life cycle greenhouse gas emission and life cycle cost of energy conversion for various energy resources. *Korean J. Chem. Eng.* **2013**, *30*, 1882–1888. [CrossRef]
92. Manesh, M.H.K.; Abadi, S.K.; Amidpour, M.; Ghalami, H.; Hamedi, M.H. New emissions targeting strategy for site utility of process industries. *Korean J. Chem. Eng.* **2013**, *30*, 796–812. [CrossRef]
93. Yu, M.; Kim, Y. Development of Environmental Assessment System of Vehicle. In *Proceedings of the FISITA 2012 World Automotive Congress*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 1151–1160.
94. Lee, J.-U.; Han, J.-H.; Lee, I.-B. A multiobjective optimization approach for CCS infrastructure considering cost and environmental impact. *Ind. Eng. Chem. Res.* **2012**, *51*, 14145–14157. [CrossRef]
95. Cho, Y.S.; Kim, J.H.; Hong, S.U.; Kim, Y. LCA application in the optimum design of high rise steel structures. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3146–3153. [CrossRef]
96. Park, J.; Tae, S.; Kim, T. Life cycle CO_2 assessment of concrete by compressive strength on construction site in Korea. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2940–2946. [CrossRef]
97. Lee, J.-Y.; Cha, K.-H.; Lim, T.-W.; Hur, T. Eco-efficiency of H_2 and fuel cell buses. *Int. J. Hydrog. Energy* **2011**, *36*, 1754–1765. [CrossRef]
98. Lee, J.-Y.; An, S.; Cha, K.; Hur, T. Life cycle environmental and economic analyses of a hydrogen station with wind energy. *Int. J. Hydrog. Energy* **2010**, *35*, 2213–2225. [CrossRef]
99. Lee, J.-Y.; Yu, M.-S.; Cha, K.-H.; Lee, S.-Y.; Lim, T.W.; Hur, T. A study on the environmental aspects of hydrogen pathways in Korea. *Int. J. Hydrog. Energy* **2009**, *34*, 8455–8467. [CrossRef]
100. Kim, J.; Hwang, Y.; Park, K. An assessment of the recycling potential of materials based on environmental and economic factors; case study in South Korea. *J. Clean. Prod.* **2009**, *17*, 1264–1271. [CrossRef]
101. Castella, P.S.; Blanc, I.; Ferrer, M.G.; Ecabert, B.; Wakeman, M.; Manson, J.-A.; Emery, D.; Han, S.-H.; Hong, J.; Jolliet, O. Integrating life cycle costs and environmental impacts of composite rail car-bodies for a Korean train. *Int. J. Life Cycle Assess.* **2009**, *14*, 429–442. [CrossRef]
102. Lee, C.; Lee, J.; Kim, Y. Comparison of environmental loads with rail track systems using simplified life cycle assessment (LCA). *WIT Trans. Built Environ.* **2008**, *101*, 367–372.
103. Lee, S.-H.; Choi, K.-I.; Osako, M.; Dong, J.-I. Evaluation of environmental burdens caused by changes of food waste management systems in Seoul, Korea. *Sci. Total Environ.* **2007**, *387*, 42–53. [CrossRef]
104. Jeong, K.M.; Hong, S.J.; Lee, J.Y.; Hur, T. Life cycle assessment on end-of-life vehicle treatment system in Korea. *J. Ind. Eng. Chem.* **2007**, *13*, 624–630.
105. Choi, B.-C.; Shin, H.-S.; Lee, S.-Y.; Hur, T. Life cycle assessment of a personal computer and its effective recycling rate (7 pp). *Int. J. Life Cycle Assess.* **2006**, *11*, 122–128. [CrossRef]
106. Lim, S.-R.; Suh, S.; Kim, J.-H.; Park, H.S.J.J.o.e.m. Urban water infrastructure optimization to reduce environmental impacts and costs. *J. Environ. Manag.* **2010**, *91*, 630–637. [CrossRef]
107. Hur, T.; Kim, I.; Yamamoto, R. Measurement of green productivity and its improvement. *J. Clean. Prod.* **2004**, *12*, 673–683. [CrossRef]
108. Lee, Y.E.; Lee, K.J.; Lee, B.W. Environmental assessment of nuclear power generation in Korea. *Prog. Nucl. Energy* **2000**, *37*, 113–118. [CrossRef]
109. Eun, J.-H.; Son, J.-H.; Moon, J.-M.; Chung, J.-S. Integration of life cycle assessment in the environmental information system. *Int. J. Life Cycle Assess.* **2009**, *14*, 364–373. [CrossRef]
110. Kang, M.-H.; Kim, S.-Y.; Park, J.-H. Strategy and Value Oriented Life Cycle Assessment: The case of Samsung Techwin Co. In Proceedings of the 2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, 12–14 December 2005; pp. 420–421.
111. Lee, J.; Cho, H.-j.; Choi, B.; Sung, J.; Lee, S.; Shin, M.J. Life cycle assessment of tractors. *Int. J. Life Cycle Assess.* **2000**, *5*, 205–208. [CrossRef]
112. MOE. Ministry of Environment. Available online: https://eng.me.go.kr/eng/web/main.do (accessed on 20 September 2020).
113. Lee, S.-S.; Kim, Y.S.; Ahn, J.W. Development of Life Cycle Inventory (LCI) Database for Production of Liquid CO_2. *Clean Technol.* **2015**, *21*, 33–38. [CrossRef]
114. Ghisellini, P.; Ripa, M.; Ulgiati, S.J. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *J. Clean. Prod.* **2018**, *178*, 618–643. [CrossRef]

115. Kim, J. The Formulation of Korea's Resource Policy: Resource Diplomacy, Public-Private Consortium and International Agreements. *Asian J. WTO & Int'l Health L & Pol'y* **2014**, *9*, 287.
116. Lee, K.; Cha, J.J.S. Towards Improved Circular Economy and Resource Security in South Korea. *Sustainability* **2021**, *13*, 17. [CrossRef]
117. OECD. *OECD Environmental Performance Reviews: Korea*; OECD Publishing: Paris, France, 2017.
118. Chau, C.K.; Leung, T.; Ng, W.Y. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Appl. Energy* **2015**, *143*, 395–413. [CrossRef]
119. Nasir, M.H.A.; Genovese, A.; Acquaye, A.A.; Koh, S.; Yamoah, F. Comparing linear and circular supply chains: A case study from the construction industry. *Int. J. Prod. Econ.* **2017**, *183*, 443–457. [CrossRef]
120. De Camillis, C.; Raggi, A.; Petti, L. Tourism LCA: State-of-the-art and perspectives. *Int. J. Life Cycle Assess.* **2010**, *15*, 148–155. [CrossRef]
121. Lenzen, M.; Sun, Y.-Y.; Faturay, F.; Ting, Y.-P.; Geschke, A.; Malik, A. The carbon footprint of global tourism. *Nat. Clim. Chang.* **2018**, *8*, 522–528. [CrossRef]
122. Holmner, Å.; Ebi, K.L.; Lazuardi, L.; Nilsson, M.J.P.O. Carbon footprint of telemedicine solutions-unexplored opportunity for reducing carbon emissions in the health sector. *PLoS ONE* **2014**, *9*, e105040. [CrossRef] [PubMed]