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Location Selection of Urban Rooftop Greenhouses in Seoul Based on AHP and GIS

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Abstract: With the recent increase in food demand, urban agriculture has gained attention as a way of increasing food self-sufficiency and providing recreational spaces in cities. In this study, the suitability of rooftop greenhouses (RGs), a type of urban agriculture, was analyzed by combining the analytical hierarchy process (AHP) and geographic information systems (GIS) in Seoul, the capital city of Korea. To achieve this, we derived location suitability factors through expert consultations and calculated the weights of each factor through AHP. After building the spatial data according to these factors, they were weighted and summed then scaled to a score of 0–100. The highest weight of the RG location factors was for benefit (0.1782), followed by officially assessed land prices (0.0913) and supermarket density (0.0802). The weights of supermarket density and accessibility were high because they are considered the main distribution channels. When analyzing the location of RGs by linking these results with the spatial data according to factor, we revealed that Gangseo-gu (a district of Seoul) had relatively high location suitability scores. This trend was determined to be caused by the rather low officially assessed land price, high supermarket density, and productive population. This result could prove useful when selecting the approximate locations of RGs in Seoul and for promoting food self-sufficiency in cities.

Keywords: urban agriculture; food mile; climate change; spatial analysis; commercial environment

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Citation: Kil, S.-H.; Park, H.-M.; Park, M.; Kim, Y.I.; Lee, E. Location Selection of Urban Rooftop Greenhouses in Seoul Based on AHP and GIS. *Land* **2023**, *12*, 2187. https://doi.org/10.3390/land12122187

Academic Editors: Hossein Azadi, David Fanfani, Gino Sturla and Benedetto Rocchi

Received: 11 October 2023
Revised: 30 November 2023
Accepted: 12 December 2023
Published: 18 December 2023

1. Introduction

According to the United Nations (UN) World population prospects report, future population growth is expected to increase food demand by 70% by 2050 [1,2]. However, as a result of recent changes in cropping systems due to climate change, outbreaks of new infectious diseases, and food security crises due to war, global food production in 2022 is expected to decrease by 1.3% compared to that in 2021 [3,4]. In response, the world is focusing on urban agriculture, which involves producing crops in cities, where more than half of the world's population is concentrated [5], to increase food self-sufficiency. Urban agriculture can be defined as the production of plants or the raising of animals for food and other uses in cities and towns [5,6]. Urban agriculture is practiced in a variety of available spaces in cities, including building rooftops, verandas, and indoor and outdoor open spaces, and contributes not only to the production of food but also to the well-being and healing needs of urban residents. However, urban agriculture has some limitations, such as the lack of space in cities, lower yields per unit area than in rural areas, and crops exposed to air pollutants.

To address these issues, rooftop greenhouses (RGs) have recently emerged as one of the main alternatives for growing crops on the rooftops of urban buildings [7,8]. The RG system involves growing crops by installing greenhouses on the rooftops of urban buildings, and it is being commercialized in developed countries in Europe and the Americas because it does not require additional land, has fewer space constraints, and enables local production and consumption based on consumer demand [8]. This system is attracting attention as a next-generation green industry to increase the food self-sufficiency rate of cities because it can stably produce high-quality crops with ICT environmental control technology within a thoroughly protected space even in the event of abnormal climatic phenomena, epidemics, and pollutants, and food miles are saved. Research on RG has been conducted in various fields since the 2010s, including life-cycle environmental impact assessment, cost–benefit analysis, efficient irrigation methods, and the circular economy [9–15].

One of the key conditions for the success of RGs in cities is location. It plays an important role in determining the economic profitability of RGs, as it determines the cost, accessibility, and potential consumers. In particular, RGs installed on building rooftops can require higher investment and maintenance costs than other urban agriculture at ground level, so it is necessary to select the right location to generate profits. The siting of RGs requires considering a combination of structural, regulatory, social, and economic factors, such as rooftop area, slope, and load. However, only a few studies have analyzed the siting of RGs while considering these factors. Berger (2013) analyzed the location of RGs by spatially analyzing the structural building factors, such as the number of floors, type, area, and year of construction, using geographic information systems (GIS) for a part of Brooklyn, New York [16]. The results revealed that buildings with high suitability scores tend to be adjacent to schools. Mendes (2008) applied Geographic Information Systems (GIS) to analyze transportation infrastructure, distribution, population density, parent city planning, and regulations to identify suitable sites for urban agriculture in Portland, Canada [17].

While studies on RG site selection are few, studies on supermarkets, grocery stores, franchise specialty stores, and shopping malls are numerous globally [18–25]. Cheng et al. (2007) presented a shopping mall location selection method using GIS by superimposing layers such as district areas, roads, railways, existing shopping mall locations, household income, and demand size in each district [20]. Shin and Moon (2011) reported that the sales of franchised coffee shops in Seoul, Korea, increased with the area and locations that provide one-stop shopping, medical care, and game viewing [22]. Roig-Tierno et al. (2013) combined the analytical hierarchy process (AHP) and GIS to analyze the best location among four sites (L1–L4) for opening a retail store in Murcia, Spain. L1 was found to be the most suitable based on the volume of passing trade, visibility, and accessibility [24].

These studies on location analysis either employed AHP to analyze the importance of major factors that affect the location or GIS to visualize these factors spatially and quantitatively. However, the former method simply lists the weights and rankings of the factors, meaning that identifying the most suitable location is difficult. In addition, general GIS spatial analysis does not consider the importance of each factor, rendering it difficult to select the right location. For example, when selecting the location for a coffee shop whose primary customer base is aged in their 20s, a GIS spatial analysis that does not weight the population according to age will skew the scores toward other age groups with larger populations, resulting in a location that does not reflect the market demand. An ideal approach for location selection would be to merge the AHP and GIS methods to extract factors affecting location, perform AHP and importance analysis for each factor, and then perform GIS spatial analysis to reflect the weights. However, using two methods would require time and effort because multiple expert surveys, big data construction for each factor in the target area, data weighting and spatialization, spatial data overlay, and other complex procedures and data would be required.

Although RGs are a major alternative to solve the recent food crisis, only a few studies on the location analysis required to do so exist. There are some studies on RGs, but they are limited to simply performing a spatial analysis through GIS without any weighting factors. Most site suitability studies have been conducted for retail stores, shopping malls, and coffee shops, and applying them to RG site analysis can lead to significant errors in the results. In addition, the few studies on RGs only consider the structural factors of buildings but ignore the macro characteristics of the city, including transportation infrastructure, or economic factors, such as land prices and rents. In this regard, our research questions are: What are the main factors affecting the suitability of RGs, and which locations in Seoul have the highest suitability scores for RGs based on these factors? To address these questions, this study analyzed the most suitable locations for RG development in Seoul, the capital of South Korea, by conducting a spatial analysis that reflects the weights of each factor through a combination of AHP and GIS. Seoul has been of high interest in related projects recently, including installing rooftop greenhouses on top of existing commercial buildings, so it is expected that the results of this study will be very useful. The results of this study can also contribute to sharing the importance of RGs internationally, by improving food self-sufficiency in cities and providing leisure space. In addition, the study can be used as a basis for selecting the location of RGs in other countries and cities, given the lack of information on the siting of RGs.

2. Materials and Methods

2.1. Study Framework

This paper consists of three main steps: (1) derivation of location selection factors and AHP analysis, (2) construction of a spatial database using location selection factors, and (3) analysis of RG location through spatial combination. Figure 1 shows the above process and framework. In this study, we first extracted the factors affecting location through a literature review of studies related to location selection and then identified the importance of each factor through expert AHP analysis. Afterward, we built a spatial database for each factor in Seoul, the subject of the study, and conducted a location analysis of RG by linking the results of the AHP analysis to it.

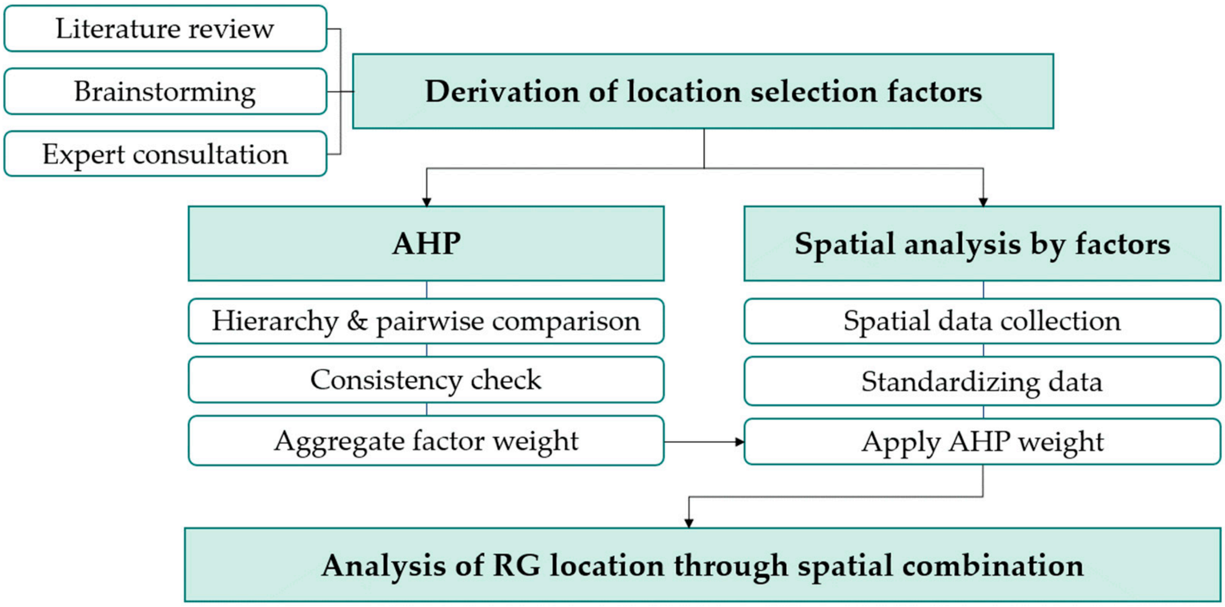

Figure 1. Systematic of the study flowchart.

2.2. Study City and RG

Seoul is the capital of Korea, located in the central-western part of the Korean Peninsula at 126–127° East longitude and 37° North latitude (Figure 2). The distances between east and west and north and south are 36.8 km and 30.3 km, respectively, and the administrative area is 605.24 km^2 [26]. It is composed of a total of 25 administrative districts, and the population and number of households were 9.7 million and 4.4 million, respectively, as of 2021. The population density is 16,086 people/km^2, which is about 1.4 times higher than that of New York City, the largest metropolitan area in the United States [26–28]. Seoul had a total of 581,257 buildings as of 2020, of which 430,608 were residential buildings, followed by 127,517 commercial buildings and 16,313 public buildings [29]. As the city of Seoul has created an RG of about 200 m^2 in a commercial building in Seongdong-gu as of 2023, and is planning to create additional RGs in hotels in Gangseo-gu in the future, it was selected as a study city because it was judged to have high interest and applicability for RGs.

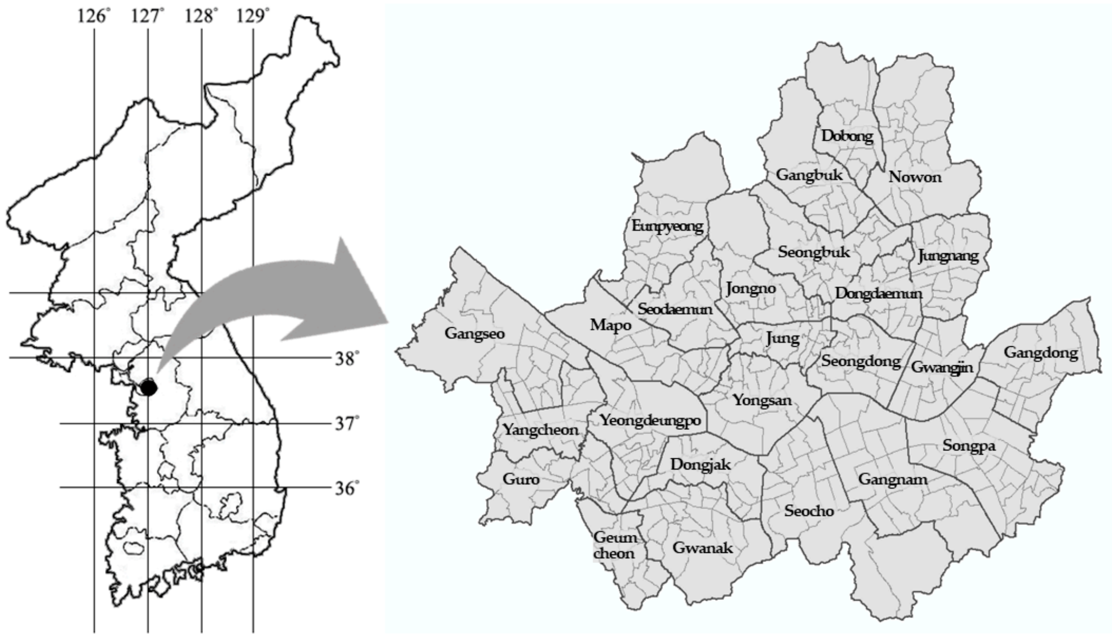

Figure 2. Location of study city.

RGs can play a positive role in increasing food self-sufficiency in a region. However, depending on the consumer, they can be categorized into models: socially based (such as weekend farms in which the food is intended for self-consumption by the local community) and commercially based (where the crops are sold to local consumers). Due to the risk of fires, RGs installed on the roofs of buildings usually employ highly fire-resistant glass as a cladding material instead of vinyl. However, the installation cost for a glass greenhouse is approximately three times higher than for a vinyl greenhouse [30]. Hence, it is currently considered unworkable for communities to invest in glass greenhouses for self-consumption without generating annual revenue. For example, Gotham greens in the United States and Cite Maraichere in France, which are representative examples of RGs, also supply their crops to local consumers in connection with large grocery stores, restaurants, and cafes [31,32]. Therefore, in this study, we focused on commercial RGs that sell crops to local consumers and conducted a location suitability analysis.

2.3. Weight Analysis by Factor through AHP

Even if location selection factors are considered, generalizing the factors without weighting can result in location selection errors. Therefore, in this study, we applied AHP to weight each factor based on the opinions of experts. AHP is a technique for hierarchically categorizing multiple factors and analyzing the importance of each factor to derive optimal alternatives. AHP can identify the main factors affecting the location of a site, and can effectively integrate expert opinions to produce reliable site selection results. It consists of the following steps: (1) establishing a hierarchical structure; (2) performing a pairwise comparison of factors; and (3) weighting and consistency checking [33,34].

In this study, we reviewed 25 studies on location selection published since 2000 [35–52] and then conducted an initial screening of relevant factors through iterative brainstorming and expert consultations. Subsequently, the final selection of RG location factors was conducted through a process of consolidation, deletion, and verification. The factors were then stratified into large, medium, and small criteria. Considering that the target of this study was RGs for commercial purposes, the 25 studies also included content related to the location of retail stores and distribution centers that sell goods.

The location selection factors were categorized into demographics, economy, and commercial environment. Demographics comprised the total population, population by age, and households; economy comprised officially assessed land prices, costs, and benefits;

and the commercial environment comprised demand conditions and accessibility. With respect to spatial analysis, these factors were further subdivided, as listed in Figure 3. The selected factors were pairwise compared with each other based on a 9-point scale, and their weights were calculated according to the level. The weights of the large, medium, and small categories were then multiplied to quantify the total weight of each factor.

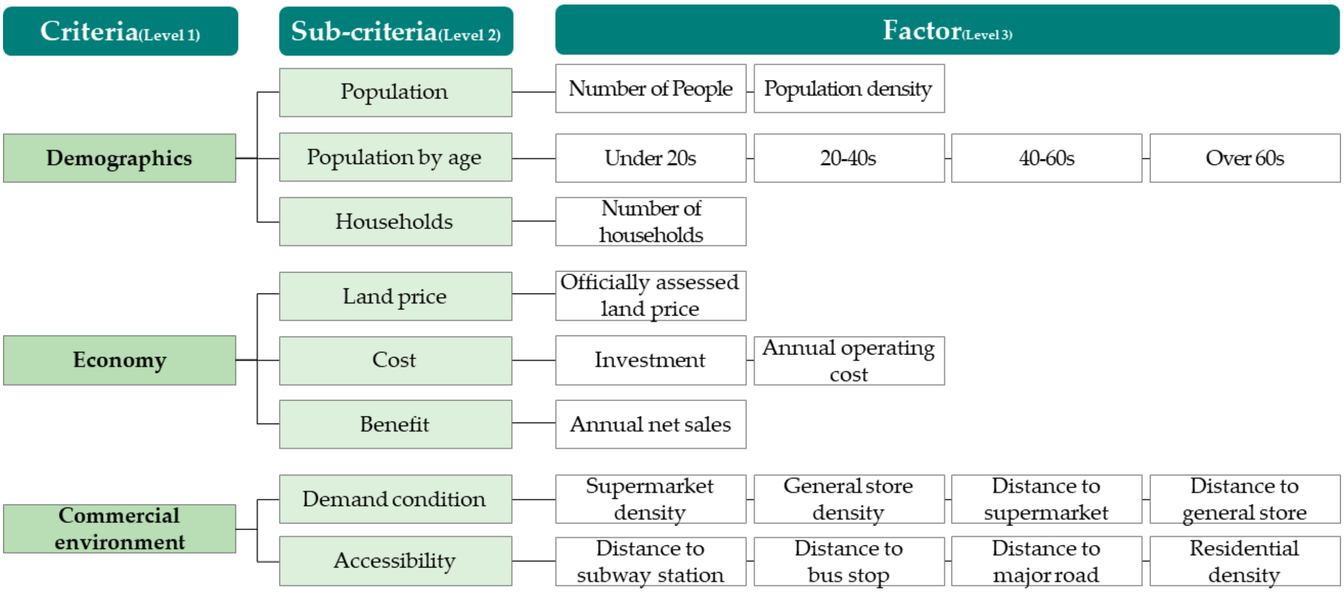

Figure 3. Factors affecting location selection of rooftop greenhouses.

On the other hand, if respondents are not consistent in their responses regarding the relative importance of each factor, the results of the analysis will be less reliable. Therefore, we calculated the consistency rate (CR) for each respondent to verify that the weights were consistent. The consistency rate is the ratio of the consistency index (CI) to the random index (RI), and the more consistent the response is, the smaller the value. In this study, we determined that a CR value of 0.1 or less is a consistent response by referring to the results of previous studies. In 2022, the AHP questionnaire was distributed to 25 relevant experts, and 20 valid responses were statistically analyzed. Meanwhile, these AHP questionnaires and statistical analyses were conducted using Microsoft Excel 2016.

2.4. Spatial Database by Factor

The above-selected factors were utilized as spatial data for GIS analysis. Table 1 lists the types of spatial data and their sources for each factor. The types of spatial data included vector formats such as points, lines, and polygons, as well as raster formats that represent distances and densities in vectors. Population density and size, population by age, and households were extracted from the Seoul Statistics Portal [53–55] by the administrative division and then matched to the spatial boundaries of the administrative division.

Regarding the economic category, officially assessed land prices were obtained from Korea's National Spatial Data Infrastructure Portal [56], and the costs and benefits of RG were obtained from information on actual projects in Seoul, interviews with relevant companies, and the literature [9–11,30,57–62]. The cost includes the installation and annual operating cost of the RG, and the benefit is the annual revenue from crop sales. Costs and benefits are highly variable depending on the type of greenhouse, materials, crops grown, and adoption programs. In this study, the default values of investment cost, operating cost, and net sales per unit area were calculated by assuming lettuce cultivation in a double-roofed glass greenhouse. Lettuce can be harvested within a month when grown hydroponically and grown year-round in stable environmental conditions and facilities [63]. This study assumes that lettuce is sown every two months and harvested six times a year.

Table 1. Spatial data types and sources by factors.

Factor	Data Type	Source
Number of people	Polygon	[53]
Population density	Polygon	[54]
Population by age	Polygon	[53]
Number of households	Polygon	[55]
Officially assessed land price	Polygon	[56]
Supermarket density	Polygon	[64]
General store density	Polygon	[64]
Distance to supermarket	Raster	[64]
Distance to general store	Raster	[64]
Distance to subway station	Raster	[65]
Distance to bus stop	Raster	[66]
Distance to major road	Raster	[67]
Residential density	Raster	[68]

To obtain spatial data, commercial and residential density and distance to supermarkets, general stores, public transportation, and main roads, we collected address data from the Local Government Permit Data Portal, National Transport Information Center, and Korea National Spatial Data Infrastructure Portal [64–68]. This text data were converted into point data by converting addresses to latitudes and longitudes using geocoding in R. The extracted points of supermarkets, general stores, subway stations, bus stops, and main roads were returned as Euclidean distances (Equation (1)) to form raster data, and their separation distances were analyzed.

$$d(X,Y) = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2} \tag{1}$$

In this equation, d is the distance between two points; x and y are the positions of the two points; and n is the number of observations. The density of supermarkets, general stores and residential sites was then calculated by applying kernel density. QGIS 3.22 and Arc Map 10.1 were used to create and analyze the spatial data. All spatial variables except costs and benefits were correlated in R using the Cor function.

2.5. Location Suitability Analysis of Rooftop Greenhouse

To analyze the suitability of the RG location in Seoul by collecting spatial data by factor, we created a 100 × 100 m grid for the entire city and extracted the values of the factor variables in each grid to form a data frame. The spacing of this grid was based on previous studies [69], considering that the one-way walking distance between residential and commercial areas in Korea is 75–100 m. Because the values in the data frame for each factor have different units, we standardized them using a min–max scale. After applying AHP weights to the standardized values of each factor, the values of all 19 variables per grid were summed. This value was scaled to return a value between 0 and 100, with higher values indicating better RG locations (Figure 4).

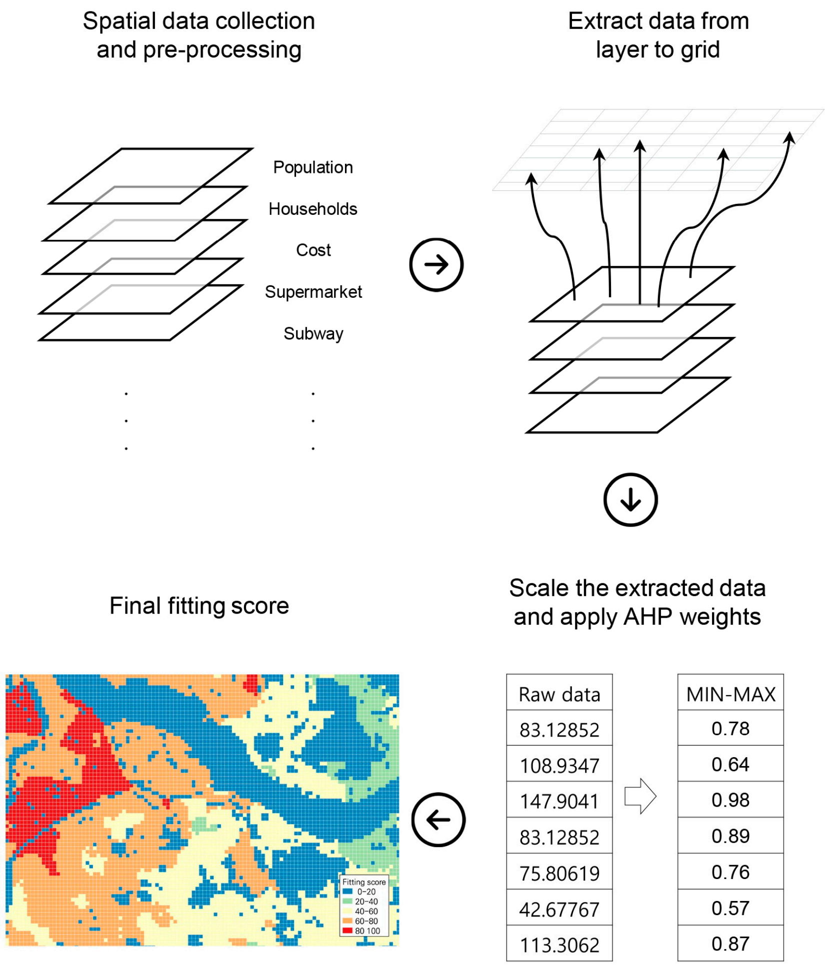

Figure 4. Process of location suitability analysis for rooftop greenhouses.

3. Results

3.1. Urban Agriculture and Vegetable Consumption in Seoul

Seoul has been practicing urban agriculture since 2011 and has been promoting projects to create vegetable gardens in various spaces in the city in addition to running related educational programs [70]. As of 2020, the area and number of urban agriculture sites in Seoul were 212 ha and 4729, respectively, which was a sevenfold increase since 2011. Within these 4729 sites, the highest proportion was rooftop gardens (1865), followed by school gardens (1539) and scrap gardens (1000). In terms of area, 8% of the total area of urban agriculture in Seoul was located on building rooftops.

The daily vegetable consumption per capita in Seoul is 261.2 g/person, which is somewhat higher than the overall average in Korea (256.0 g/person) [71]. Based on this information, the estimated annual vegetable consumption in Seoul was approximately 930,000 t/year. Considering that Seoul's annual self-sufficient vegetable production is approximately 0.25 t/year [26], the demand for vegetables by Seoul residents far exceeds local production. However, because Seoul is mostly urban, securing additional space for crop production (including vegetables) is challenging. Therefore, RGs are necessary for improving food self-sufficiency in Seoul.

3.2. Weights by Factor

Our analysis of the weights for each factor in the large category revealed that the economy was the highest at 0.3838, followed by the commercial environment at 0.3746 and demographics at 0.2416 (Table 2). Breaking down these factors, the economy was analyzed in the order of benefits (0.4443) > costs (0.2796) > land prices (0.2762), the commercial environment was analyzed in the order of demand conditions (0.7324) > accessibility (0.2676), and demographics were analyzed in the order of population by age (0.4473), population (0.3219), and households (0.2308). When analyzing the weights by tier, annual net sales (0.1782) were the highest, followed by officially assessed land prices (0.0913), supermarket density (0.0802), distance to supermarket (0.0747), operating costs (0.0668), general store density (0.0656), and distance to general store (0.0574).

Table 2. Weighting and ranking by factor.

Criteria	Weights	Sub-Criteria	Weights	Factor	Weights	Ranking
Demographics	0.2416	Population	0.3219	Number of people	0.0215	17
				Population density	0.0485	10
		Population by age	0.4473	Under 20s	0.0097	19
				20–40s	0.0243	16
				40–60s	0.0244	15
				Over 60s	0.0179	18
		Households	0.2308	Number of households	0.0465	11
Economy	0.3838	Land price	0.2762	Officially assessed land price	0.0913	2
		Cost	0.2796	Investment	0.0547	8
				Annual operating cost	0.0668	5
		Benefit	0.4443	Annual net sales	0.1782	1
Commercial environment	0.3746	Demand condition	0.7324	Supermarket density	0.0802	3
				General store density	0.0656	6
				Distance to supermarket	0.0747	4
				Distance to general store	0.0574	7
		Accessibility	0.2676	Distance to subway station	0.0326	12
				Distance to bus stop	0.0257	14
				Distance to major road	0.0519	9
				Residential density	0.0281	13

3.3. Characteristics of Spatial Distribution by Factor

3.3.1. Demographics

In Seoul, the population size, population by age, and households were generally higher in Gangseo-gu, Eunpyeong-gu, Gangnam-gu, Nowon-gu, and Gwanak-gu (Figure 5). The population of people in their 20–60s, who are expected to be the main demand groups for rooftop greenhouses, tended to be somewhat higher in Gangnam-gu, Songpa-gu, and Gangseo-gu, respectively. On the other hand, Dongdaemun-gu, Yangcheon-gu, and Dongjak-gu had the highest population densities, whereas Gangseo-gu and Eunpyeong-gu, which had large populations, tended to have lower population densities. This is because population density is determined by area in addition to the number of people. In fact, Gangseo-gu and Eunpyeong-gu are the second and sixth largest districts in Seoul, respectively, and are at least 1.7 and up to 2.9 times larger than Dongdaemun-gu and Yangcheon-gu, respectively.

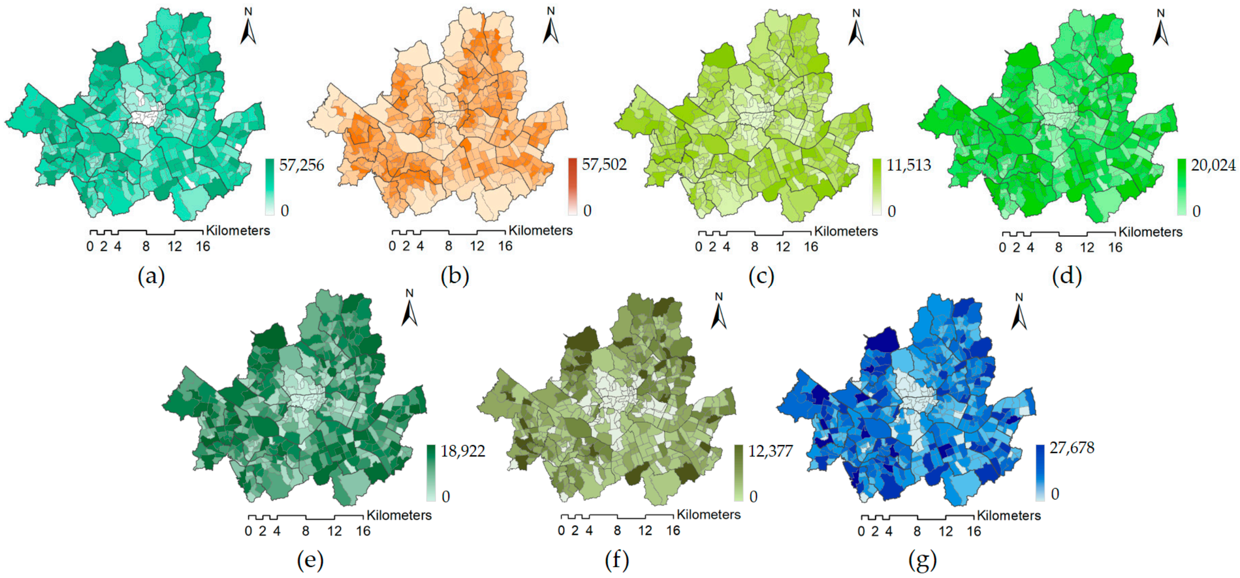

Figure 5. Spatial analysis of demographics in Seoul. (**a**) Number of people; (**b**) Population density; (**c**) Under 20s; (**d**) 20–40s; (**e**) 40–60s; (**f**) Over 60s; (**g**) Households.

3.3.2. Economy

Officially assessed land prices in Seoul ranged from a minimum of 420 to a maximum of 149,800 USD/m^2, with an average of 7300 $\pm$ 50.5 USD/m^2 (Figure 6). Land prices tended to be high in Gangnam-gu, Seocho-gu, and Jung-gu. We used the median investment cost per unit area for RGs based on existing international precedents (230–764 USD/m^2) [9,11,57,58]. This is approximately 497 USD/m^2, which is 1.8 times higher than the cost of installing a glass greenhouse in Korea of 280 USD/m^2. Rooftop greenhouse installation requires heavy equipment to transport materials to the rooftop, which is more expensive than ground-level installation. On the other hand, it is generally accepted that glass greenhouses are at least 1.3 and up to 3.6 times more expensive than film and vinyl greenhouses, respectively [30]. This unit cost is based on glass greenhouses, and the investment cost may vary depending on the actual greenhouse covering material. However, because the rooftop of a building is subject to stronger winds and dryness than the ground, glass greenhouses are deemed desirable in terms of durability. According to the Rural Development Administration (2022), the annual operating costs and revenue per unit area of lettuce in facilities based on one harvest per year were 4 USD/m^2 and 7 USD/m^2, respectively [60]. Based on this data, assuming six harvests of lettuce per year, the annual operating costs and revenue per unit area were analyzed to be 19 USD/m^2 and 44 USD/m^2, respectively. These investment costs, operating costs, and benefits per unit area were applied to a 100 $\times$ 100 m grid.

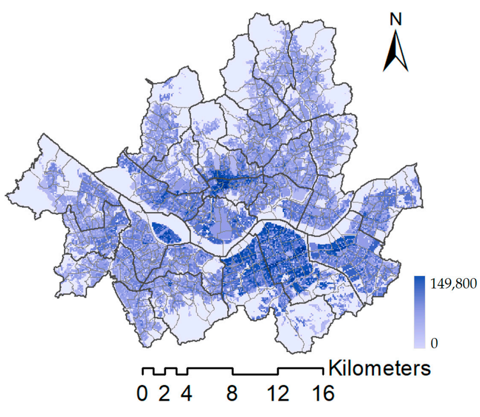

Figure 6. Spatial analysis of officially assessed land prices in Seoul (Unit: USD/m^2).

3.3.3. Commercial Environment

There were approximately 51 supermarkets and 12,172 general stores in Seoul as of 2021 [64]. These markets can be a major outlet for the crops produced in RGs. In Seoul, the distance to supermarkets and general stores tends to increase as one moves to the outskirts of the city (Figure 7). The concentration of supermarkets is mainly high in Seongdong-gu, Dongdaemun-gu, Jungnang-gu, and Nowon-gu in the east and Yeongdeungpo-gu, Yangcheon-gu, Mapo-gu, and Gangseo-gu in the west. The density of general stores was high throughout the center of the city and tended to decrease outward. Seoul has approximately 387 subway stations and 11,315 bus stops [65,66]. Distances to subway stations and bus stops decreased as one moved to the outskirts of the city, with similar trends for distances to major roads. Residential density was high throughout the city's interior.

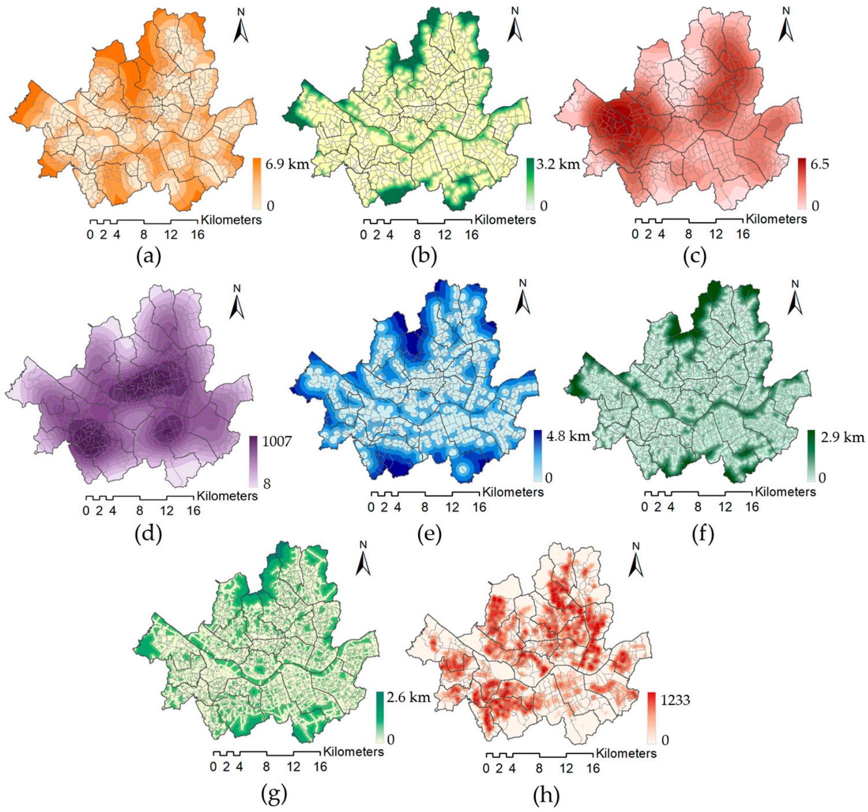

Figure 7. Spatial analysis of commercial environment in Seoul. (**a**) Supermarket density; (**b**) General store density; (**c**) Distance to supermarket; (**d**) Distance to general store; (**e**) Distance to subway station; (**f**) Distance to bus stop; (**g**) Distance to major road; (**h**) Residential density.

3.3.4. Correlation by Factors

If a location suitability analysis includes many factors that are highly correlated with each other, it can be difficult to interpret which factors have a strong impact on suitability, reducing the reliability of the analysis results. To avoid this situation, the correlation between the factors of location suitability was analyzed, as displayed in Figure 8. As a result, the correlation coefficients between the number of people, the number of people by age, and the number of households ranged from 0.43 to 0.95, indicating a high positive correlation ($p < 0.01$). In comparison, other factors were generally analyzed to have low correlations. This result suggested that most factors could be included in a site suitability analysis, with the exception of population/social variables. In comparison, even though population, population by age, and households were somewhat highly correlated, the experts suggested that it would be desirable to link them together because population according to age can reflect the demand group that will primarily use RGs. Moreover, households are a factor related to residential characteristics in addition to population.

Therefore, these factors were also considered in the location analysis. The mentioned experts were the same researchers who participated in the AHP weighting.

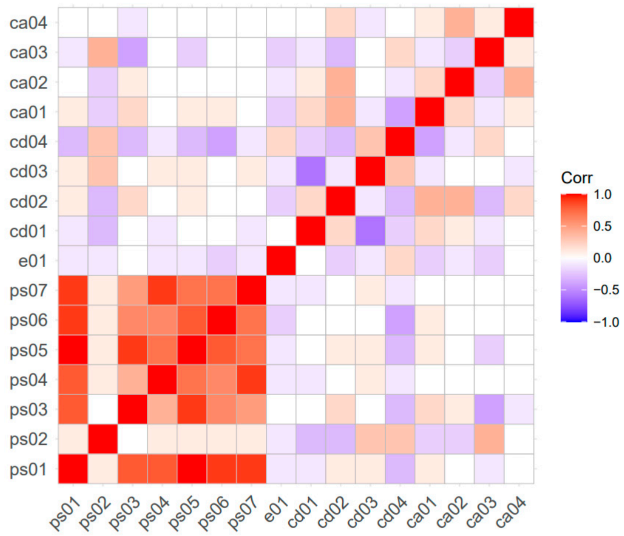

Figure 8. Correlation by factors of rooftop greenhouses. **(ps01)** Number of people; **(ps02)** Population density; **(ps03)** Under 20; **(ps04)** 20–40s; **(ps05)** 40–60s; **(ps06)** Over 60s; **(ps07)** Households; **(e01)** Officially assessed land prices; **(cd01)** Supermarket density; **(cd02)** General store density; **(cd03)** Distance to supermarket; **(cd04)** Distance to general store; **(ca01)** Distance to subway station; **(ca02)** Distance to bus stop; **(ca03)** Distance to major road; **(ca04)** Residential density.

3.4. Location Suitability of Rooftop Greenhouse

Figure 9 shows the results of the RG site selection analysis by linking the weights of each factor with the spatial database. The location suitability score of the RG averaged 31.6 ± 0.1 points, with a distribution of 45.8% below 30 points, 29.8% between 50 and 70 points, 15.1% between 30 and 50 points, and 9.3% above 70 points. In Seoul, the districts that included neighborhoods with location suitability scores of 80 or more were Gangseo-gu, Yeongdeungpo-gu, Yangcheon-gu, Guro-gu, Eunpyeong-gu, Dongdaemun-gu, Seongbuk-gu, and Seongdong-gu. These neighborhoods had a high concentration of supermarkets and were close to subway stations, bus stops, and main roads. Additionally, they had large populations, households, and relatively low officially assessed land prices. Of these, Seongdong-gu is currently installing RGs on the rooftops of commercial buildings, and Gangseo-gu plans to start related projects in 2024.

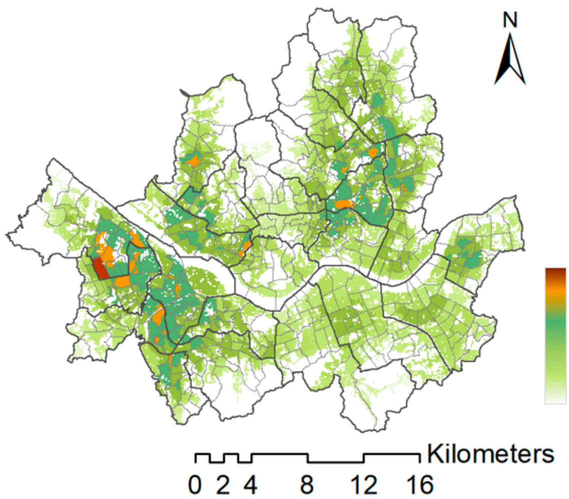

Figure 9. Location suitability of rooftop greenhouses in Seoul.

4. Discussion

4.1. Factors Affecting the Location of Rooftop Greenhouses

Various factors contribute to a successful location selection. However, these factors may vary in importance depending on the type of business, destination, and natural and social environment. In the commercial-based RGs of this study, the top five factors with the highest weighting were benefit, officially assessed land price, supermarket density, distance to supermarket, and operating costs. Roig-Tierno et al. (2013) reported that among the location selection factors for retail stores in Spain, the volume of passing trade, visibility, distance from competition, potential market, accessibility by car, accessibility by foot, and brand recognition have high weights [24]. Among the location selection factors for Korean franchise coffee shops, the most important factors were store location, location in the shopping district, foot traffic, proximity to public transportation, development of the shopping district, fixed costs, and exchangeability [22].

Although not based on the same study, previous studies, including this one, have tended to consider cost and accessibility as key location selection factors to increase benefits. The high weighting of market density and accessibility in this study is likely because they are considered the main source of demand for crops grown in RGs. Indeed, market access can contribute to a company's profit, and if the production site and market are close to each other, most of the transportation costs can be saved. On the other hand, the districts with the highest location suitability scores in this study were Gangseo-gu, which were influenced by the officially assessed land prices and supermarket density. Notably, this district has a high concentration of supermarkets and relatively low land prices. In addition, transportation accessibility, residential density, population, and households were found to have some influence on the location selection, although their weights were somewhat lower. In other words, the closer a location was to major roads, subway stations, and bus stops, and the more people in the 20–40- and 40–60-year age groups, the higher the suitability scores.

4.2. Differences in Location Suitability Based on Analysis Method

In this study, we compared the results of GIS location analysis without factor weighting and a weighted GIS analysis (Figure 10). The results indicated that the locations of neighborhoods with the highest suitability scores tended to be similar, while other neighborhoods exhibited differences in their scores of up to 5.6 times ($p < 0.01$). For example, weighting increased the scores of neighborhoods with a high concentration of supermarkets, while unweighting tended to decrease the scores of these neighborhoods. In addition, when the weighting was applied to areas with high officially assessed land prices, the score decreased. However, when the weighting was excluded, the score tended to be relatively higher. This result suggested that due to the nature of commercial RGs, which are intended to increase the profit-to-investment ratio, the cost of the investment may increase more than the profit due to errors in location selection. Therefore, it is recommended to apply weights that are consistent with the characteristics of the RG to produce appropriate results during location analysis.

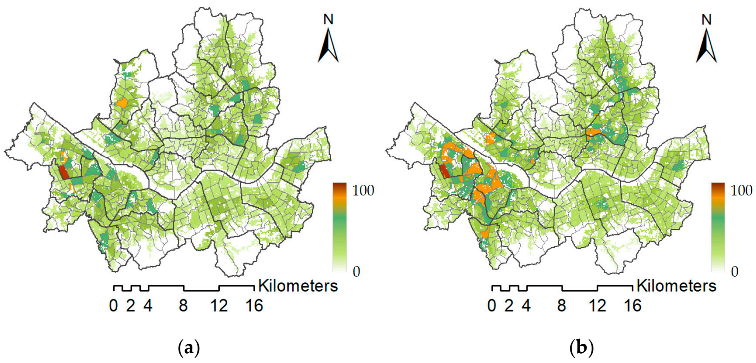

Figure 10. Differences in location suitability based on analysis method. (**a**) General GIS spatial analysis; (**b**) AHP + GIS analysis.

4.3. Limitation of This Study

Our findings are subject to the following limitations. First, information about individual buildings was not considered. Although the location may be highly suitable, it may be difficult to conduct the actual business due to the durability of the building, floor area ratio, building coverage ratio, and related regulations. These findings should be leveraged to select approximate business locations rather than RG locations for individual buildings. In the future, a system that can review building information and related regulations for individual buildings together after selecting an approximate business location through this study should be developed.

Second, we applied the same costs and benefits to each grid. Unlike the other siting factors, which have separate values within a grid, the costs and benefits are all set to the same value. As mentioned in the methodology, RGs are highly variable, depending on greenhouse shape, area, materials, crops grown, and adoption programs. Currently, it is not possible to introduce costs and benefits according to the type of RG by grid, and it is necessary to improve this aspect in the future by comprehensively reviewing the residual floor area ratio, building coverage ratio, and sunlight from adjacent buildings.

Third, we did not consider the type of social-based RGs for self-consumption by local communities. In this study, only commercially based RGs were selected as the subject of the study because we judged that there were limitations in operating RGs for self-consumption with only government subsidies without revenue generation. In future work, it would be necessary to pursue the community model of self-consumption through the development of affordable RG installation technology and to expand the location analysis according to RG type by setting appropriate location factors and weights.

4.4. Opportunities and Directions for RG in Urban Agriculture

Cities, which are home to more than half of the world's population, rely heavily on food from outside their regions. This means that when unforeseen disasters, including typhoons, earthquakes, and pandemics such as the coronavirus occur, the supply of food from the outside world to cities can be disrupted. Urban agriculture is an opportunity to expand urban foodsheds and food self-sufficiency. However, in Korea and around the world, urban agriculture is constrained by a lack of space and high land costs. In this regard, RGs, which produce food by installing greenhouses on the rooftops of urban buildings, are considered an opportunity to revitalize urban agriculture while solving the space shortage. While home gardens can be established on the rooftops of buildings, greenhouses, which can grow more crops per unit area uniformly regardless of disasters, seasons, and air pollution, may be more desirable for urban food production. In fact, on rooftops in Barcelona, Spain, tomato yields per unit area in greenhouses were up to 1.4–3.8 times higher than in conventional gardens [10,72–75].

However, RGs are still facing difficulties in their application due to the absence of supportive policies, lack of building coverage ratio, and high installation costs. To solve these problems, we propose the following measures. First, RGs are incorporated into certification systems, such as green buildings and carbon footprint, and incentives are provided for such buildings. Incentives can include tax reductions and relaxation of building height and floor area ratios. Second, it lays the groundwork for realizing RGs, including guidelines for the installation and operation of RGs and laws on weekly leases between operators and buildings. RG guidelines should include types of RGs based on building use, such as commercial, public, and residential. Third, some financial support for RG installation should be provided, such as grants, low-interest loans, and volunteer labor. Fourth, a governance structure should be established to provide operators with integrated support for RGs, including education, technology, and policies. Fifth, the development of new technologies for RGs that minimize installation costs while maximizing benefits should be actively pursued. These technologies may include maximizing production per unit area, incorporating multiproduct varieties, planting new high-value crops, recycling RG waste materials, and installing new durable and economical greenhouse coverings.

5. Conclusions

In response to global issues such as the food crisis and changing cropping systems due to climate change, there has been a growing interest in RGs, which involve growing crops in greenhouses on the rooftops of urban buildings. RGs can be more costly than other types of urban agriculture conducted at the ground level, so proper siting is required to generate profits. However, unlike supermarkets and general stores, there is little research on the siting of RGs. Therefore, this study analyzed the appropriateness of RG locations by combining AHP and GIS in Seoul.

The focus of this study was RGs that sell crops to local consumers for commercial purposes rather than for self-consumption. To identify the factors that influence the location of these RGs, we applied the AHP technique to collect the opinions of experts. As a result, the weight of RG location factors was highest for benefit (0.1782), followed by officially assessed land price (0.0913), supermarket density (0.0802), distance to supermarket (0.0747), operation cost (0.0668), general store density (0.0656), and distance to general store (0.0574). The high weighting of market density and accessibility in this study is likely due to these being the main outlets for the crops grown.

When analyzing the location of RGs by linking the weighted results of location selection factors and spatial data by factor, we found that in Seoul, Gangseo-gu has relatively high location suitability scores. This trend is likely due to officially assessed land prices, supermarket density, and distance to supermarkets. This district had somewhat lower officially assessed land prices and a higher density of supermarkets. In contrast, when the location analysis was performed without applying weighting through AHP, the regions with the highest scores were analyzed somewhat similarly, although other regions exhibited differences in scores of up to a factor of 5.6. This result suggested that it is necessary to apply weights according to the characteristics of the location to derive appropriate results.

The results of this study can be used as the basis for a selection methodology that could determine appropriate locations for RGs in other countries and cities besides Seoul. However, this study is limited, as information and regulations such as durability, floor area ratio, and building coverage ratio of individual buildings are excluded, and the same costs and benefits are applied to each grid. In the future, the siting analysis of RGs should be refined on a building-by-building basis by comprehensively considering the load, floor area ratio, building coverage ratio, sunlight from neighboring buildings, and costs and benefits of individual buildings. In addition, to promote the field applicability of RGs in cities, an institutional foundation, including incentives, financial support, and governance, should be established and new technologies to promote economic efficiency should be developed.

Author Contributions: Conceptualization, S.-H.K. and H.-M.P.; methodology, S.-H.K. and H.-M.P.; software, M.P.; formal analysis, M.P.; writing—original draft preparation, S.-H.K. and H.-M.P.; writing—review and editing, S.-H.K. and H.-M.P.; visualization, M.P. and Y.I.K.; supervision, S.-H.K. and E.L.; project administration, E.L. All authors have read and agreed to the published version of the manuscript.

Funding: Please add: This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20212020800050).

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Minkyu Park is employed by DHNENC Co., Ltd. The authors declare no conflict of interest.

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