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Eco-Friendly Technology Derivation and Planning for Rooftop Greenhouse Smart Farm

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Abstract: Rooftop greenhouse-type smart farms are a promising solution to the climate and food crises because they can utilize waste heat and CO_2 from buildings for plant growth and supply fresh produce to urban areas at a low price. However, legal and structural constraints make it difficult to expand existing rooftops to accommodate smart farms, and standardized glass greenhouses are often installed as is, which may not be the most efficient or eco-friendly approach. The purpose of this study is to present a plan for integrating eco-friendly technologies between buildings and smart farms. In the study, 214 eco-friendly and smart farm cases were collected, and a database was built from the perspective of the environment and eco-friendly technology for plant growth. Thirty experts from architects, professors, and greenhouse installation companies were evaluated to determine which eco-friendly technologies can be applied to smart farms. From a building integration perspective, eco-friendly technologies applicable to smart farms were derived from a plant growth perspective. Based on the derived eco-friendly elements, it can be used in planning a rooftop greenhouse-type smart farm.

Keywords: urban agriculture; vertical farm; smart farm; rooftop greenhouse; facility horticulture; passive techniques

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1. Introduction

1.1. Study Background and Objectives

Today's society is facing a food crisis owing to climate change, urbanization, low birth rates, and aging populations [1–3]. Urbanization has led to urban sprawl, which contributes to environmental pollutants and carbon emissions, as well as a decrease in farmland and farming manpower [3–6]. Furthermore, carbon emissions are causing global warming, creating an environment where it is difficult for crops to grow gradually [7,8]. In Korea, the population is concentrated in metropolitan areas because of the lack of land area, and low birth rates and societal aging are becoming more severe, creating a high likelihood that the country will face a severe food crisis [1–3]. Problems with food distribution have become evident after the recent pandemic and international disputes, and there is a growing need to increase food self-sufficiency regionally [9–11].

The installation of smart farms on urban building roofs is attracting attention as a means of dealing with climate and food crises; previous studies have shown promising results [5–8,12–19]. Because this method utilizes unused rooftop spaces in cities, there is a vast area that can potentially be cultivated, and fresh, locally grown crops can be provided at low prices [5–7,13,20–25]. In addition, the waste heat and CO_2 that are generated by building heating and cooling can be used as resources for growing plants, and rooftop farms can reduce the heating and cooling loads within buildings [5–8,13,26]. However, in Korea, when greenhouses are added to building rooftops as additional stories, practical issues arise, which make installation difficult owing to structural and legal constraints. Therefore, urban farms are often installed in indoor spaces rather than on rooftops. In buildings where floorspace is available and structural stability is ensured, the design standards for rooftop greenhouses are unclear even after going through the complex permitting process for adding a greenhouse as an extra storey. Therefore, gable-type or Venlo glass greenhouses that are usually installed outdoors are often placed on roofs as is, and in many cases, they are not integrated into the existing building in terms of function or appearance.

Currently, there are many practical constraints on adding rooftop greenhouse smart farms as extra stories owing to the present laws and regulations. However, as the advantages of such farms steadily become clear both in Korea and abroad and regulations such as floor area ratios and design standards are consequently relaxed, the potential for rooftop smart farms to proliferate and expand is quite significant [27]. As such, it is necessary to consider the addition of smart farms as extra stories so that they are integrated with the existing buildings in terms of aspects such as space, form, environment, structure, and facilities. Particularly, rather than separately installing eco-friendly technologies in the building and greenhouse, it is necessary to consider methods that can integrate and connect these elements. This is because eco-friendly technologies in the field of construction, which aim to provide human habitation, and eco-friendly technologies in the field of horticulture, which aim to grow crops, have been developed with different purposes and perspectives. To simultaneously realize these two different objectives, it is necessary to implement environmental functions and design integration by expanding eco-friendly technologies that have been applied to buildings for application in greenhouses.

Therefore, this study aims to present a planning method for eco-friendly technologies that are integrated with rooftop greenhouse smart farms.

1.2. Study Methods and Process

First, this study collected examples of smart farms and normal buildings that use eco-friendly technology in Korea and abroad (Figure 1). The examples were collected from the Internet and literature, including 130 examples of smart farm buildings in Korea and abroad and 84 examples of eco-friendly buildings, for a total of 214 examples. Smart farms and eco-friendly building cases are applying eco-friendly technologies from different perspectives of plant growth and human comfort. Therefore, only cases where technical elements related to environmental control could be identified were collected. In addition, a classification system for eco-friendly technologies related to plant growth was established so that cases from different perspectives could be integrated and constructed. A database was constructed for 214 cases by classifying natural elements, applicable technologies, and application effects. The 214 cases were divided into active technologies (10) and passive technologies (23), and 30 experts evaluated whether 33 technological elements could be applied to smart farms. The expert evaluation results were derived through basic statistical analysis, and a planning strategy for eco-friendly technology combined with a rooftop greenhouse-type smart farm was presented.

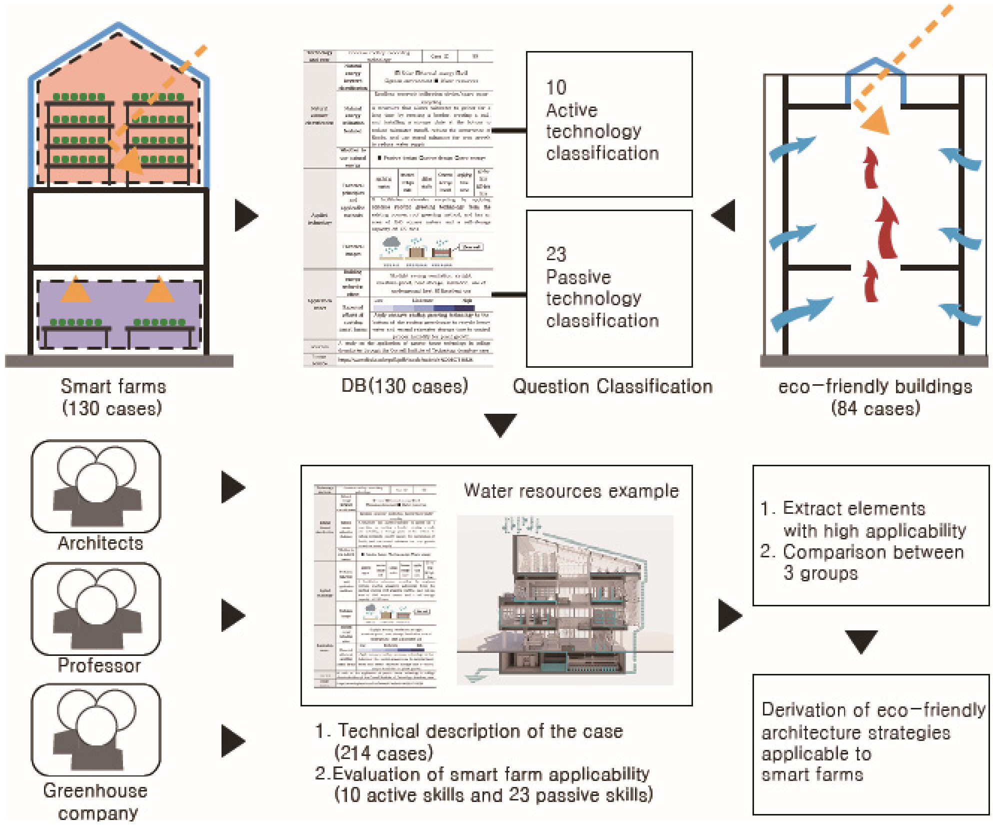


Figure 1. Research flow.

2. Theoretical Considerations

2.1. Concept and Definition of Smart Farms

Before the introduction of the smart farm concept to address the climate and food crisis, the concept of vertical farming was first introduced. Vertical farming is a concept that aims to address the problems of population, food supply, and urbanization through high-density urban crop production, and it was first proposed by Gilbert Ellis Bailey in 1915 [12]. In the mid-1980s, researchers established vertical farming systems while studying optimized agricultural production systems based on the concept of an optimal region, time, and formula. After the concept was popularized by Dickson Despommier in the early 2000s, urban and vertical farming became established as a means of dealing with climate change and food crises [5–7]. In the 2000s, advances in IoT technology allowed sensor- and device-based automated precision farming technology to be applied in vertical farming, which gave rise to the term “smart farm”.

A smart farm refers to a farm that uses a system that is interconnected via IoT technology to measure the crop environment’s temperature, humidity, carbon dioxide, soil, and sunlight and provide nutrients or control the environment such that plants can grow [28]. A variety of cultivation styles are used, including soil cultivation, hydroponics, aeroponics, and aquaponics [13]. Of these styles, the hydroponic method is generally used because it increases the crop’s growth density by setting up multilevel growth beds. Smart farms include sensors to measure the environment, devices to supply nutrient solutions, LED lighting, ventilation, and heating and cooling equipment, which are integrated via a control system. Smart farms have the benefit of significantly reducing manpower using IoT technology and allowing crops to be grown easily through data, even by those who lack agricultural knowledge. In addition, they are more productive than conventional farms, and in terms of maintenance, it is known that stable operations and profitability are possible [29].

Gotham Green in the United States has constructed a large-scale, glass greenhouse that utilizes hydroponics to cultivate crops while optimizing energy efficiency through smart technology [30]. Vertical Harvest Jackson, which connects residential, commercial, and community facilities with its multi-story growing space, operates within a building [31]. In Canada, Verticrop exemplifies the utilization of rooftop space for plant cultivation. Employing a conveyor-belt growth bed and an environmental control system, Verticrop maximizes crop production on top of parking lots [32]. Germany's REWE Supermarket (ECF) implements an aquaponics system that recycles rainwater to nurture both plants and fish [33]. Sky Greens in Singapore boasts 38 layers of high-rise hydroponic growing beds, achieving maximum production within a limited area [34].

As a form of urban farming, smart farms have been demonstrated to have social, economic, and environmental benefits in several studies. First, smart farms allow for a variety of activities in addition to their productive functions, such as social exchange, relaxation, leisure, education, and experiences [35]. Local residents form communities through activities such as growing, harvesting, and selling crops at smart farms, which can lead to a sense of local pride, and socially vulnerable people may be provided with employment [13,14,18,19,36,37]. Secondly, smart farms can provide produce at stable prices and reduce the carbon emissions and costs that result from the use of transportation because crops that are produced in urban areas can be directly harvested as needed and provided to the local community at a low cost [13,17]. Finally, in terms of the environment, smart farms allow for environmentally clean crop cultivation and reduced building energy usage. Because the crops are grown in a controlled environment, they can be protected from environmental pollution and grown without effects from the environment [13,23,38]. In addition, the placement of greenhouses on rooftops can alleviate the city heat island effect and reduce the building's heating and cooling energy loads, as well as help to purify the air [39–43]. Specifically, the waste heat and carbon dioxide that are generated by building heating and cooling can be used for crop production, which can reduce carbon emissions [13].

2.2. Smart Farm Architecture Types

There are a variety of smart farm architecture types. Shon et al. collected cases of Korean and overseas smart farms and classified their architectural features into seven types based on urban/suburban location, building scale, growth space density, applied location, use of natural light, and degree of smart technology utilization [44]. It is easier to secure land in suburban regions than in urban regions; therefore, suburban smart farms are often operated at a large scale, and these are divided into glass greenhouses that utilize sunlight and factory-type smart farms that do not receive sunlight but uniformly control the environment. Urban smart farms are divided into smart farms that operate on a small scale indoors, rooftop greenhouse smart farms, and smart farms where crops are planted on the building envelope. Indoor smart farms use container boxes or unused urban land and are operated on a small scale of 500 m^2 or less, and like factory-type smart farms, they do not receive sunlight; therefore, crops are cultivated in a controlled environment. Rooftop smart farms are installed as extra stories on the roofs of commercial and residential buildings and use a glass envelope so that they can actively receive sunlight. Both types of smart farms cultivate plants at high densities in multilevel growth beds and rely heavily on IoT technology.

In South Korea, there has been a trend of gradual expansion of smart farms owing to government policy projects. Smart farm innovation valleys have been created throughout the country, and support projects have been actively carried out to allow the young population to settle in farming and fishing villages [45,46]. The establishment of four "Smart Farm Innovation Valleys" across Korea fosters an infrastructure encompassing growth, research, education, and accommodation, aimed at disseminating smart farm technology throughout society [45,46]. Various types of smart farms have begun to appear in the private sector as well. Jincheon Root Square aimed to incorporate various programs into a smart farm, such as exhibitions, experiences, leisure, and accommodation, in addition to the productive functions of the smart farm [47]. There are cases of smart farms being operated at large supermarkets and cafes to provide customers with fresh produce. The Sangdo Station Metro Farm is a smart farm that was created by the City of Seoul, Seoul Metro, and Farm8 in an unused indoor space at Sangdo Station, which provides a space for growing crops, research, production, sales, education and experiences, and relaxation [48,49].

However, smart farms in urban areas have mainly consisted of small-scale indoor smart farms rather than rooftop greenhouse smart farms. Other than the case of the rooftop greenhouse smart farm empirical project that is being conducted as a part of a national R&D project, there are few examples of greenhouses being installed as rooftop greenhouses in South Korea. This is because the installation of a greenhouse as an extra storey on an existing building requires adherence to legal conditions such as floor area ratios and limits on the number of stories, and structural reviews must also be completed. When rooftop greenhouses are installed in Korea and abroad, the gable-type or Venlo glass greenhouses that are commonly used outdoors are often placed on the roofs as is. Therefore, it is necessary to consider the addition of an extra storey in a way that considers integration with the existing building in terms of space, form, environment, structure, and facilities.

2.3. Eco-friendly Techniques for Smart Farms

The eco-friendly construction plans for smart farm construction in Korea and abroad vary according to the type of smart farm. The Sangdo Station Metro Farm in Korea is an indoor smart farm that blocks out the external environment; therefore, it has the benefit of requiring a smaller winter energy load than glass greenhouses, which are exposed to the outdoors, and the maintenance of a uniform indoor growing environment [49]. Because it utilizes unused space in a subway station, it can be considered eco-friendly in terms of space usage costs and space utilization [49]. The KT mushroom growing dome house minimizes the area of openings and creates a highly insulated and highly airtight indoor space to block out sunlight and heat energy and create a mushroom growing environment that does not need natural light. Airtightness was ensured by assembling compressed Styrofoam and covering the joints with urethane foam, and heating and cooling were provided by a control system in a controlled environment. Canada's Sky Farm plan presents a concept in which eco-friendly technology is actively used in a high-rise building that incorporates commercial facilities and an urban farm. The flow of heat and sunlight into the building is adequately blocked using hydroponics on the building's 55-storey envelope [50]. BIPV (Building Integrated Photovoltaic System) and wind power generation facilities are installed on the roof, and power is generated by burning agricultural waste [50]. In addition, city sewage is purified and used as agricultural water, and the moisture that occurs during the cultivation process is used as drinking water [50]. Underground tubes and equipment shafts are used to maximize the natural ventilation performance [50]. The Cité Maraîchère smart farm in France consists of two buildings with steel structures and glass envelopes and is used for vertical cultivation, sales, and education [51]. Each building includes an atrium to maximize the temperature difference ventilation, and outdoor air is allowed to flow into the buildings when necessary [51]. For natural light, the buildings' envelopes are covered in glass, and stormwater is collected and used as agricultural water [51]. The Korea Institute of Machinery and Materials smart farm is an experimental greenhouse on the roof of a building, and it uses eco-friendly facilities that are being developed at the research center [52]. The waste heat and carbon dioxide that are generated by the heating and cooling facilities are supplied to the greenhouse, and light barriers are installed to control sunlight [52].

Considering the eco-friendly technology that can be used according to the type of smart farm, passive and active technology are used depending on the crop growing conditions. The use of envelope materials and insulation is determined by the two approaches by which external environmental factors are blocked out or allowed in. In addition, there are passive and active techniques that aim to utilize external environmental conditions such as sunlight, heat, wind, stormwater, etc.

3. Deriving Eco-friendly Technology for Rooftop Greenhouse Smart Farms

3.1. Method of Collecting and Analyzing Examples

Through the Internet and literature, 130 smart farms and 84 eco-friendly building cases were collected. Among smart farm cases, cases that did not address eco-friendly technology were excluded, and cases in which it was difficult to identify technological elements in eco-friendly building cases were excluded. To describe the growth conditions and eco-friendly technologies of 214 cases, the cases were organized by dividing them into natural elements, applied technologies, and applied effects. Seven review meetings were held from August to December 2022 to understand the principles of eco-friendly technology and plant growth and to input accurate information. Based on 214 databases, active items (10 items) and passive items (23 items) were distinguished, and an evaluation sheet was created asking whether 33 technologies applied to smart farms.

For the evaluation, 30 experts who knew the concept of smart farms or had project experience were selected. A survey was conducted twice with a total of 30 experts, including 14 architects, 6 professors, and 10 companies. The first evaluation was conducted on 9 people in September 2023, and the second evaluation was conducted on 21 people in January 2024. A simple question and answer was asked about whether 33 active and passive technologies can be applied to smart farms, but to ensure an accurate understanding of the technology, all 214 technological elements were explained and questions and answers were asked about each concept. When answering the survey, the respondent was asked questions about each of the 33 items and was given enough time to answer by referring to the technical overview and related cases (Figure 2). Responses to the questionnaire were answered on a 5-point Likert scale. A score of 1 is "very unlikely to apply", a score of 3 is "moderate", and a score of 5 is "highly applicable".

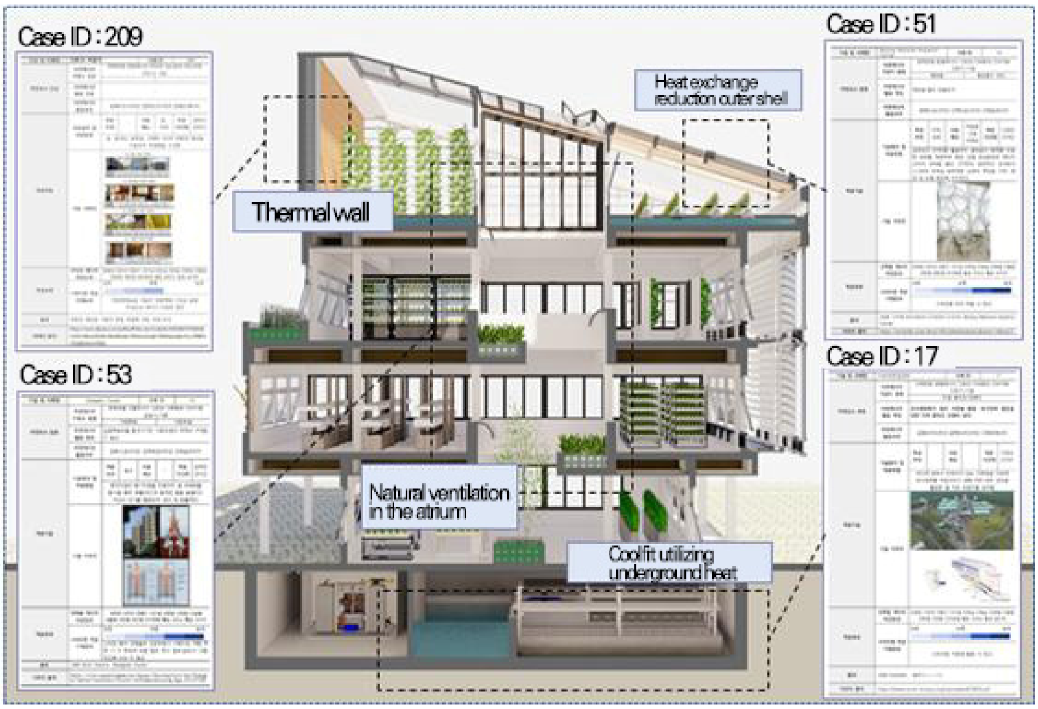


Figure 2. Example image for evaluation showing eco-friendly technology elements for each part.

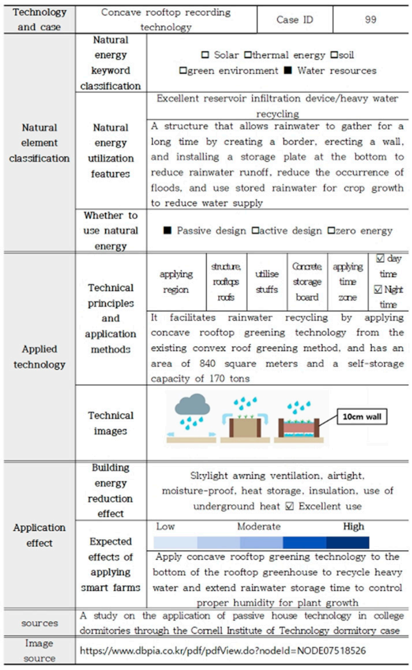
For the evaluation results of 30 people, the overall average and comparison between groups were determined through simple basic statistical analysis. Through the survey results, the feasibility of applying eco-friendly techniques to smart farms was identified, and an application strategy was presented.

3.2. Eco-Friendly Technology Classification System Database

The classification system for the database of the collected examples broadly consists of (1) natural elements, (2) applied technologies, and (3) effects of application (Table 1). The 214 cases were divided into natural elements and technologies so that both cases applied to smart farms and eco-friendly buildings could be described. If it is simply described as an eco-friendly technology, it is difficult to understand its relationship with natural elements. Therefore, it is necessary to understand what natural elements and eco-friendly elements are related to.

Table 1. DB classification system and examples.

Natural Elements	Keyword Classification	Solar Heat/Thermal Energy/Soil/Green Environment/Water Resources/Air
	Features of Use	Characteristics of Natural Energy Utilization by Case Description
	Method of Use	Passive Design/Active Design/Zero Energy
	Eco-Friendly Design	Insulation/Blocking Moisture/Solar Heat Gain/Blocking Solar Heat/Ventilation, Ventilation/Evaporative Cooling/Radiant Cooling/Mechanical Cooling/Dehumidification (Duplicate Check)
Applied Technology	Technical Principles and Application Methods	Application Area, Materials Used, Application Time Describes Technical Principles and Application Methods
	Technology Images	Representative Images of Passive Architectural Plans and Passive Technology Elements Are Attached.
Effect of Application	Green Building Certification Evaluation Item Linkage	Land Use and Transportation/Energy and Environmental Pollution/Materials and Resources/Water Cycle Management/Maintenance/Ecological Environment/Indoor Environment
	Expected Effects of Smart Farm Application	Smart Farm Applicability Divided Into 5 Levels: 'Low'/'Medium'/'High' Prioritize The Connectivity of Green Building Certification Evaluation Items
	Evaluation of Smart Farm Applicability	Describe in Detail the Assessment of Smart Farm Applicability



Technology and case		Concave rooftop recording technology			Case ID	99	
Natural element classification	Natural energy keyword classification	☐ Solar ☐thermal energy ☐soil ☐green environment ■ Water resources					
	Natural energy utilization features	Excellent reservoir infiltration device/heavy water recycling					
		A structure that allows rainwater to gather for a long time by creating a border, erecting a wall, and installing a storage plate at the bottom to reduce rainwater runoff, reduce the occurrence of floods, and use stored rainwater for crop growth to reduce water supply					
	Whether to use natural energy	■ Passive design ☐active design ☐zero energy					
Applied technology	Technical principles and application methods	applying region	structure, rooftops roofs	utilise stuffs	Concrete, storage board	applying time zone	☑ day time ☑ Night time
		It facilitates rainwater recycling by applying concave rooftop greening technology from the existing convex roof greening method, and has an area of 840 square meters and a self-storage capacity of 170 tons					
	Technical images	10cm wall					
Application effect	Building energy reduction effect	Skylight awning ventilation, airtight, moisture-proof, heat storage, insulation, use of underground heat ☑ Excellent use					
	Expected effects of applying smart farms	Low Moderate High					
		Apply concave rooftop greening technology to the bottom of the rooftop greenhouse to recycle heavy water and extend rainwater storage time to control proper humidity for plant growth					
sources		A study on the application of passive house technology in college dormitories through the Cornell Institute of Technology dormitory case					
Image source		https://www.dbpia.co.kr/pdf/pdfView.do?nodeId=NODE07518526					

First, the natural energy-related keywords and energy usage methods were classified in the Natural Elements category, and their usage characteristics were described. Next, the technical principles, application methods, and images were placed in the Applied Technology category. Finally, the Effect of Application category consists of methods for reviewing green building certification evaluation item integration and evaluating and describing smart farm applicability.

Similar to LEED in the US and BREEAM in the UK, Korea has an eco-friendly building certification system called G-SEED (Green Standard for Energy and Environmental Design) [53]. Currently, smart farms have no direct relationship with G-SEED certification. However, because smart farm buildings cover a lot of eco-friendly technology elements, there is a very high possibility of obtaining certification in the future. This is a realistic approach for the expansion of smart farms because obtaining certification can result in deregulation. Therefore, it is necessary to review whether the eco-friendly technology in the case can be applied to G-SEED and whether the classification criteria follow the standards of G-SEED. In the Effect of Application category, items from seven specialist fields (land use and transportation, energy and environmental pollutants, materials and resources, water cycle management, maintenance, ecological environment, and indoor environment) were included to review the green building certification (G-SEED) applicability.

The 214 examples were classified as active or passive technology based on five natural elements, and the results for the examples are listed in Appendices A and B. Eco-friendly technology is applied in various ways within the five natural elements, and among the smart farm examples, there was a high proportion of eco-friendly technology that uses sunlight and stormwater; however, it was found that there is a movement to use eco-friendly technology from a similar perspective as normal eco-friendly buildings.

3.3. Evaluation Results

Expert evaluations based on a 5-point Likert scale show the possibility of applying and expanding eco-friendly building technology to rooftop smart farms (Figure 3; Appendix B). Most eco-friendly technologies received high scores (3.98 points), while elements that block light (louvers, window size, special glass) or elements unrelated to greenhouses (staircase ventilation, flooring, indoor space ratio) received relatively low scores.

Among them, atrium (4.7), high-performance envelope structure (4.67), building form and direction (4.60), and infrared absorbing glass (4.53) received high evaluations. These elements are passive technologies that can achieve eco-friendly effects in terms of architectural planning, material performance, and functionality. The atrium is an element that induces ventilation by planning a void space inside the building. However, it shows that there is a high possibility that the same elements can be applied to plant growth spaces or utilized in conjunction with the building atrium. The amount of solar radiation or energy load varies depending on the shape or direction of the building and is indicated as an element that can be applied to smart farms to maximize plant growth. Meanwhile, high-performance outer shell structures and infrared-absorbing glass show high potential for use as elements for reducing energy load in smart farms.

There are differences between the three expert groups. The overall rating by the group is in the order of professor (4.28), architect (4.19), and greenhouse installation company (3.52). While university professors are generally positive about the applicability of eco-friendly technology, greenhouse companies that actually carry out construction on-site show relatively low results.

The items that these groups commonly gave high ratings for were high-performance envelope structure, building form and direction, and infrared-absorbing glass. Meanwhile, PV panels (solar power generation), which are widely used in architectural design, were evaluated highly by architects (4.7), while greenhouse installation companies received very low scores (3.3). In addition, the evaluation of greenhouse companies such as biomass use energy production, geothermal heat pump, nutrient solution supply, sunroom, geothermal cool pit/trench, wall, window, etc. was low.

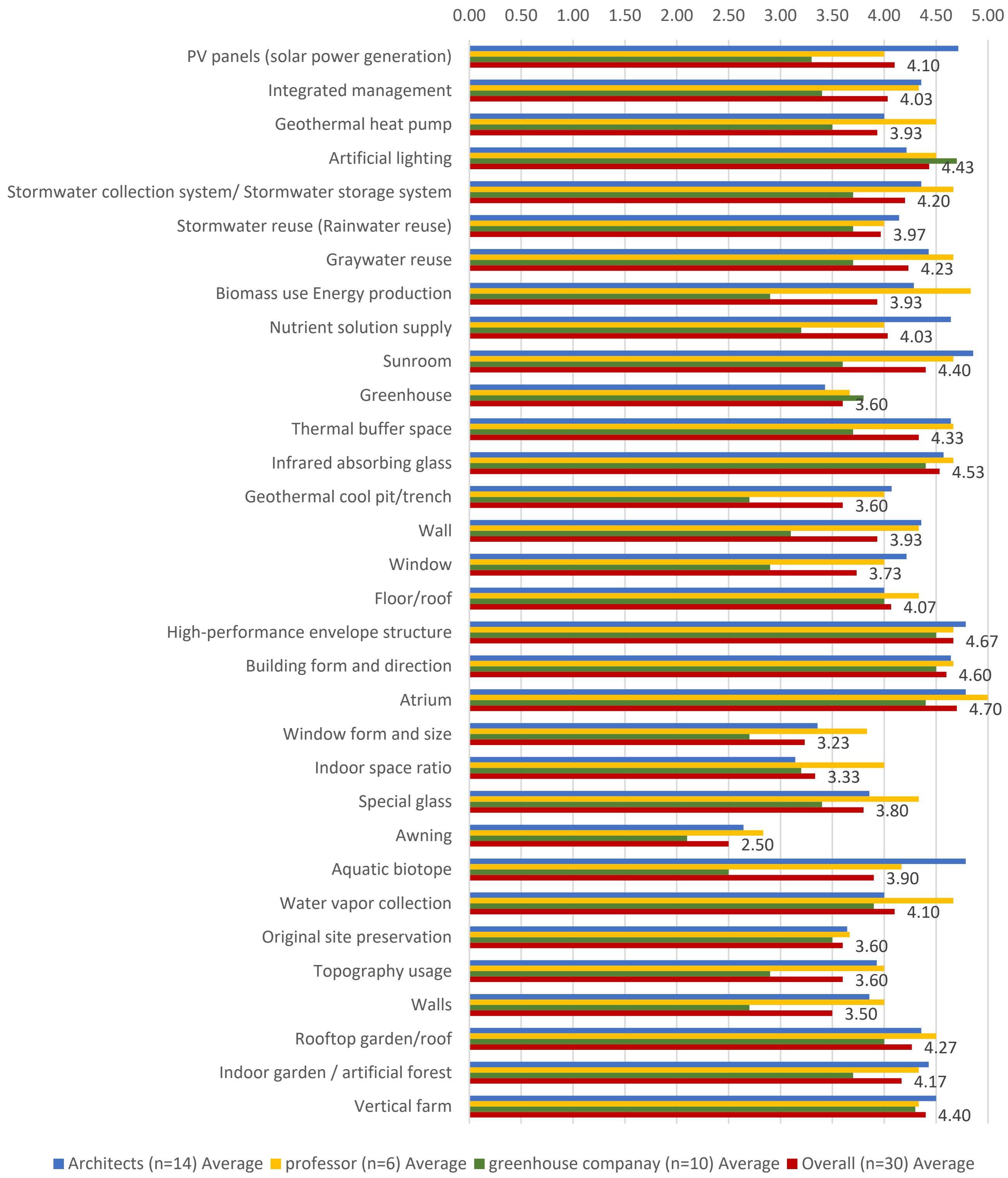


Figure 3. Expert evaluation results (average).

4. Rooftop Greenhouse Smart Farm Eco-Friendly Technology Strategies

4.1. Eco-Friendly Technology from a Plant Growth Perspective

Technologies with a high possibility of application on smart farms were derived from the previously created eco-friendly architecture database. However, rather than directly applying eco-friendly technology to greenhouses, it is necessary to classify technology elements more specifically from the perspective of an environment for growing plants. The environmental elements for plant growth were classified into four types (light intensity, temperature, humidity, and airflow) to subclassify the eco-friendly technologies that were evaluated as being better than normal in the database.

The basic growth conditions for plants consist of photosynthesis, respiration, and transpiration. Photosynthesis is a process by which plants obtain CO_2 from the air and create carbohydrates and oxygen together with water. In photosynthesis, the right levels of light, CO_2, and temperature are important factors. Respiration is a process by which plants convert carbohydrates into the energy needed to maintain themselves and transform the remaining carbohydrates into plant tissue. It occurs at high temperatures; therefore, temperature is an important factor. Transpiration refers to the effect by which water escapes through pores on the backs of leaves, and it also serves to draw water up from the roots and stems to the leaves for photosynthesis. Sufficient transpiration is made possible by suitable temperatures and a strong metabolism; light intensity, temperature, and humidity are also important factors.

The temperatures at which plant growth is most active are between 10 and 30 degrees, and growth temperatures vary according to the plant. The minimum limit temperature at which growth stops is 13 degrees, and the maximum limit temperature is 30 degrees, which prevents root growth. Moisture accounts for approximately 70–90% of the elements that make up plants, and suitable temperatures are maintained through the evaporation of moisture from the leaves. Nutrients that are absorbed at the roots are dissolved to become raw material for photosynthesis. Light is necessary for the photosynthesis process, which creates carbohydrates from carbon dioxide and moisture, and growth efficiency varies according to the strength or weakness of sunlight. Wind stimulates the leaves and promotes photosynthetic activity and moisture evaporation; therefore, air can be circulated to remove moisture, maintain suitable humidity, and create an environment in which active gas exchange can occur.

In Table 2, the eco-friendly elements that are applicable to smart farms are classified according to the environmental factors for plant growth.

The elements that affect the temperature were confirmed to be the placement of core elements on the north side of the building, considering the northwesterly winds that occur during the winter, as well as controlling the window area, insulation, and eco-friendly elements that use geothermal heat. When considering urban smart farm examples that consist solely of glass greenhouses, it is deduced that environmental performance feasibility can be demonstrated if these eco-friendly elements are applied.

In the case of humidity, there are eco-friendly technologies that control humidity through stormwater, ventilation, and materials. Methods for controlling humidity through stormwater and ventilation are commonly used techniques in existing smart farm examples; however, there are no cases of controlling humidity through laminates. The feasibility of the methods that use materials to appropriately control humidity was demonstrated.

4.2. Deriving Eco-Friendly Technologies for Application on Smart Farms

In the case of light intensity, there are two techniques: allowing natural light to flow in and blocking natural light. The goal of glass greenhouses is to maximize the inflow of sunlight; however, in the summer, the temperatures in glass greenhouses can become excessive because of sunlight, and techniques are presented to appropriately control sunlight through special glass, double glazing, double envelopes, and louvers. In particular, when there are multilevel growth beds in greenhouses, it can be difficult for the sunlight to reach the floor area, and it is deduced that uniform light intensity can be provided through light shelves, etc.

In the case of airflow, elements such as double envelopes, atriums, and indoor/outdoor temperature difference ventilations are presented. In the smart farm examples, some examples induce ventilation through atriums or open windows and doors during transitional seasons, and in controlled indoor environments, there are many examples that operate ventilation fans. In cases where windows are opened during transition seasons, the temperature difference ventilation can be applied, which maximizes the transpiration effects through ventilation even without the use of ventilation fans.

Therefore, eco-friendly building technologies that are highly applicable when smart farms are integrated into buildings have been derived. However, it is necessary to use eco-friendly technologies that are suitable for the building's indoor and outdoor installation locations and methods.

Table 2. Four crop growth environmental factors and eco-friendly technology factors.

Category		Temperature	Humidity	Light	Airflow
Architecture plan elements	Building Form		• Roof greenification: rainwater reuse, collection	• Sawtooth roof: introduce natural light	• Convex, concave building form: control airflow
	Room, placement plan	• Place core at the north, place growing space at the south		• Place core at the north, place growing space at the south	
	Window area ratio	• Reduce window area: reduce heat loss • Increase window area: increase heat capture	• Windows and doors facing each other: Control humidity through cross-ventilation • Openable windows and doors: control humidity through opening	• Reduce window area: decrease light • Increase window area: increase light	• Windows and doors facing each other: control airflow through cross-ventilation • Openable windows and doors: control airflow through the opening
	Louvers, awnings, blinds		• Laminate use: control humidity	• Fixed window awnings • Outer wall panel	
	Double glazing	• Double glazing, triple glazing: prevent excessive heat load indoors		• Special glass: block harmful sunlight	
	High insulation	• Floor and wall heat storage: radiation (emission)			
	Double envelope	• Use ETFE(Ethylene tetrafluoroethylene) envelope: resist temperature changes	• Porous envelope: exchange water	• Double skin: control light during summer and winter	• Double skin: circulate air inside and outside the building
	Building greenification	• Envelope greenification: block infrared rays	• Roof greenification (rooftop greenification): collect and reuse rainwater		
Passive plan elements	Natural ventilation				• Atrium: circulate air through the chimney effect
	Geothermal heat use	• Geothermal heat exchange equipment • Cool heat tube			
	Solar heat use	• Install solar heat panel on northern façade • Solar panels (cooling and heating)		• Northern opening plan: maximize the inflow of natural light	• Badgir: ventilation using the temperature difference between outdoor and indoor air
	Rainwater reuse		• Circulate water within the building • Underground rainwater storage equipment		
	Natural light			• Light shelves: indoor light control • Light ducts: indoor light control	

This study aims to present a plan based on the eco-friendly technologies that are highly applicable to smart farms that were derived in Section 3. Figure 4 is an example image in which a building and a rooftop smart farm are integrated through eco-friendly technologies.

Figure 4. Image of rooftop greenhouse-type smart farm plan.

The rooftop greenhouse smart farm's eco-friendly technology plan uses active and passive technology simultaneously. First, passive technology arranges the building elements, provides insulation and airtightness, blocks and allows the inflow of sunlight, maximizes ventilation performance during transition seasons, and manages humidity through stormwater use. Next, the active technology uses BIPV and PV for solar heating and solar power generation, utilizes ground heat, stores heat in stormwater storage tanks, etc.

If there is a common space, such as an atrium or a hall, in an existing building, the effects of ventilation and natural lighting can be improved through plans that allow the two spaces to be connected by removing part of the roof slab. It may also become easier to connect the spatial programs between the existing building and the greenhouse because the moving lines are connected. The effect of ventilation may increase as the temperature difference effect increases because the building and atrium are connected, and plans can also be prepared to allow the oxygen that is emitted by plants during photosynthesis to flow into the building's interior space.

The waste heat and carbon dioxide that are generated by the machine room can be used as energy sources for growing plants in the greenhouse, and more efficient energy use is possible by storing stormwater in the machine room. The stormwater that is stored in the water tank can be used to supply water or control humidity in the greenhouse, and solar heat, geothermal heat, and waste heat that occurs during heating and cooling can be stored in the stormwater and utilized. Recently, aquaponics-type smart farms have been introduced, and energy can also be used to raise fish and aquatic plants in the water tank.

Greenhouses that are installed on roofs generally use glass materials with high energy performance and are constructed to be highly airtight; however, insulation can be used on the northern side to block cold winds in the winter and reduce the heating load, and louvers can be installed to control sunlight in the summer and reduce the cooling load. In general, glass greenhouses serve to create a warm indoor environment by blocking cold winter winds and allowing maximum sunlight to enter. However, in the summer, glass greenhouses have the disadvantage of raising interior temperatures to excessive levels; therefore, it is necessary to prevent temperature increases by installing louvers at suitable locations to block sunlight. In addition, if a material that is capable of reflecting light is used as the louver material, it can serve to transmit sunlight to places where sunlight has difficulty reaching because the lower parts of the growth beds are shaded.

Not all rooftop greenhouses are wrapped in material that allows sunlight to pass through, such as glass. In spaces where mushrooms are grown and spaces that are used by humans, such as spaces for processing crops, it is necessary to block the sunlight adequately. In such cases, BIPV can be installed to generate energy while simultaneously blocking sunlight and heat.

As such, rooftop greenhouse smart farms can be created so that the existing building and eco-friendly technologies are integrated, rather than creating the building and the greenhouse as independent forms.

5. Conclusions

There is growing interest in the creation of smart farms in unused spaces on the rooftops of urban buildings to achieve self-sufficient food production and reductions in building heating and cooling loads. To date, there have been few cases of rooftop greenhouses because there are legal and structural constraints on installing greenhouses on rooftops, and it is necessary to go through a complex permitting process. However, owing to the advantages of urban farming and smart farms, it is likely that rooftop greenhouse smart farms will soon proliferate, spread, and become established as a new type of architecture in our society.

However, in many examples of smart farms in Korea and abroad, glass greenhouses that are used outdoors are installed on rooftops as is, and the building and greenhouse are each used independently. When adding a greenhouse as an extra storey, it is necessary to consider the program integration in accordance with the existing building's purpose, design integration with the exterior, and environmental and energy integration with the existing building to maximize the smart farm's role in responding to climate and food crises. In particular, eco-friendly technology must be planned from the perspective of integrating the building and rooftop greenhouse smart farm because the building and greenhouse are each developed with different purposes and perspectives. The waste heat and carbon dioxide that are generated when heating and cooling the building can be supplied to the greenhouse, or fresh air that is generated in the greenhouse can be supplied to the building. In addition, summer and winter heating and cooling loads can be reduced, the city heat island effect can be mitigated, and the air quality can be improved.

This study examined the feasibility of integrating existing buildings with smart farms through eco-friendly technologies and presented an approach by which such technologies can be applied. Examples of smart farms that use eco-friendly technology and examples of normal buildings in Korea and abroad were collected, and the operating principles of the eco-friendly technologies were classified according to natural elements. Subsequently, technologies with high applicability to smart farms were selected through expert evaluations and classified into four types of plant growth environmental factors to present a plan for eco-friendly technologies that are integrated with rooftop greenhouse smart farms. Through expert evaluation by architects, professors, and greenhouse installation companies, eco-friendly technologies applicable to smart farms were derived. While identifying eco-friendly technologies commonly presented by expert groups, we also discovered technologies that showed differences in perceptions of applicability between groups.

Greenhouses and buildings have different purposes: habitation and crop growth. However, even a combination of buildings with different purposes shows the possibility of integrating eco-friendly technologies. Through energy circulation, energy load can be reduced, space usability can be maximized, and exterior design unity can be achieved. Once eco-friendly technology performance is secured, it is advantageous to obtain eco-friendly certification such as G-SEED, and it is expected to contribute to the distribution and expansion of rooftop greenhouse-type smart farms in the future.

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Appendix A. Active and Passive Technical Elements Shown in the Case

Plan Element		Active Technical Elements Feature
Solar heat	PV panels (solar power generation)	Building energy conservation through solar heat generation Installation of panels that consider best direction and method for receiving sunlight Converting energy that is captured during daytime and using it at nighttime Building energy conservation through building integrated solar power generation
	Integrated management	Controlling temperature, humidity, CO_2, etc. via automated systems
Heat energy	Geothermal heat pump	Underground buried geothermal pipes and geothermal heat pumps
	Artificial lighting	Introduction of artificial lighting to provide constant insolation
Water resources	Stormwater collection system/ Stormwater storage system	Creating boundaries, building walls, and installing rainwater detention tank at the bottom to reduce occurrence of flooding by reducing rainwater runoff through structures that allow rainwater to stagnate for long periods of time Advanced irrigation and rainwater collection system Storing rainwater that is collected from rooftops in underground water tanks and reusing it Green roofs that include rainwater storage systems
	Stormwater reuse (Rainwater reuse)	Reducing service water use using stored rainwater for growing crops Pipe system for rainwater stored during evaporative cooling process Reusing water to grow plants in rooftop garden through underground pipe system that reuses rainwater collected from greenified roof
	Graywater reuse	Reusing wastewater that is filtered in building to maintain plants on greenified walls Reusing wastewater that is used in building and using it as irrigation water for building garden Purifying and reusing water that is used for irrigation
Green environment	Biomass use Energy production	Reducing energy used in building through electricity production by burning farming waste that is generated during plant cultivation
		Using biomass as plant nutrients
	Nutrient solution supply	Introducing technology such as nutrient solution supply and remote environment control

Plan Element			Passive Technical Elements Feature
Solar heat	Solar heat	Sunroom	Buffer space between interior and exterior and transition space between indoors and outdoors
		Greenhouse	Ventilation tower utilizing stairwell
		Thermal buffer space	Plant growing space that is separate from living space and acts as a thermal buffer space between indoors and outdoors
		Infrared absorbing glass	Infrared absorbing insulating glass
	Geothermal cool pit/trench		Use of ground heat that has narrow range of temperature change, installation of underground cool pit trench to reduce fresh air load Passive cooling via cool heat tube using ground heat Reduction of building energy consumption through heat exchange between building and ground via heat absorbing liquid circulation system that uses underground water tank
	Insulation	Wall	Building cooling energy reduction using walls with high insulation performance Condensation control and heat bridge prevention using highly insulating walls
		Window	Facilitating ventilation of building's internal space using openable windows with high insulation performance
		Floor/roof	Ground cover to aid in temperature control, waterproof coating protection, and rainwater absorption
		High-performance envelope structure	Transparent envelope covered in plants that have air-purifying effect
Thermal energy	Building form and direction		Adjustment of building's placement and form according to direction of sunlight Planning building form to maximize sunlight received Planning building form to create suitable indoor thermal environment by controlling excessive sunlight
	Natural light	Atrium	Receiving sunlight through the form and placement of the atrium Planning atrium as space for growing plants and indoor garden Natural light and ventilation effect of atrium which creates chimney effect
		Window form and size	Increasing energy efficiency by combining various forms of windows Environment control effect through windows that can change form Maximizing natural light by increasing window ratio
	Indoor space ratio		Ratio of highly green spaces and plant gardens within building
	Special glass		Prevention of building heat increases using special glass with thermal properties Blocking harmful infrared rays and some ultraviolet rays
	Awning		Awning effect of plants on building envelope (envelope greenification) Prevention of indoor heat overload through awnings over windows and doors Use of awnings to control how sunlight is received according to direction (louvers and blinds)
Water resources	Aquatic biotope		Use of biomass as plant nutrients
	Water vapor collection		Changing seawater into freshwater by adopting Namibian beetles' technique for collecting water in desert
Soil energy	Original site preservation		Maintaining nearby wetlands and green spaces by considering environmental effects of building
	Topography usage		Reducing heating load during winter and reducing cooling load during summer using inclination of natural topography to plan building at the ground Creating outdoor farming spaces using natural topography (terraced topography)
Green environment	Building greenification	Walls	Conserving growing space using vertical structures such as walls and columns Purifying air through planting and wall greenification, and reducing city heat island effect through surfaces that supply oxygen, control humidity, and absorb heat Blocking inflow of excessive sunlight through shielding function that uses plants on building facade Reducing noise pollution exposure using plants on building facade Building façade greenification that considers biodiversity Balconies and terraces that allow planting
		Rooftop garden/roof	Connecting indoor and outdoor spaces through roof greenification Evaporation cooling effect through roof greenification Green rooftops Various edible plants harvested from rooftop garden Rooftop greenhouse hydroponics
		Indoor garden/artificial forest	Creation of semi-permanent green structures by installing vertical gardens on large tree-shaped structures with built-in solar cells Outdoor landscape spaces created to connect with interior atriums In-site landscaped spaces planned at large ratios
		Vertical farm	Vertical farms that regulate the building's overall environment by blocking direct sunlight and purifying air Receiving sufficient sunshine through rotating plant trays Increasing productivity and preventing unnecessary land use through stacked plant trays Controlling positions within vertical farm according to crop type

Appendix B. Expert Survey Results

Contents	Architects (n = 14)		Professor (n = 6)		Greenhouse Company (n = 10)		Overall (n = 30)	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
PV panels (solar power generation)	4.71	0.469	4.00	0.632	3.30	0.675	4.10	0.845
Integrated management	4.36	0.745	4.33	0.816	3.40	0.516	4.03	0.809
Geothermal heat pump	4.00	0.784	4.50	0.548	3.50	0.527	3.93	0.740
Artificial lighting	4.21	0.699	4.50	0.837	4.70	0.483	4.43	0.679
Stormwater collection system/ Stormwater storage system	4.36	0.842	4.67	0.516	3.70	0.483	4.20	0.761
Stormwater reuse (Rainwater reuse)	4.14	0.663	4.00	0.632	3.70	0.675	3.97	0.669
Graywater reuse	4.43	0.646	4.67	0.516	3.70	0.483	4.23	0.679
Biomass use Energy production	4.29	0.726	4.83	0.408	2.90	0.568	3.93	0.980
Nutrient solution supply	4.64	0.497	4.00	0.632	3.20	0.632	4.03	0.850
Sunroom	4.86	0.363	4.67	0.516	3.60	0.516	4.40	0.724
Greenhouse	3.43	1.089	3.67	0.816	3.80	0.789	3.60	0.932
Thermal buffer space	4.64	0.497	4.67	0.516	3.70	0.483	4.33	0.661
Infrared absorbing glass	4.57	0.646	4.67	0.516	4.40	0.699	4.53	0.629
Geothermal cool pit/trench	4.07	0.730	4.00	0.632	2.70	0.483	3.60	0.894
Wall	4.36	0.633	4.33	0.516	3.10	0.738	3.93	0.868
Window	4.21	0.699	4.00	0.894	2.90	0.738	3.73	0.944
Floor/roof	4.00	0.555	4.33	0.516	4.00	0.667	4.07	0.583
High-performance envelope structure	4.79	0.426	4.67	0.516	4.50	0.527	4.67	0.479
Building form and direction	4.64	0.497	4.67	0.516	4.50	0.527	4.60	0.498
Atrium	4.79	0.426	5.00	0.000	4.40	0.516	4.70	0.466
Window form and size	3.36	0.497	3.83	0.408	2.70	0.675	3.23	0.679
Indoor space ratio	3.14	0.663	4.00	0.632	3.20	0.632	3.33	0.711
Special glass	3.86	1.027	4.33	0.816	3.40	0.516	3.80	0.887
Awning	2.64	0.633	2.83	0.753	2.10	0.568	2.50	0.682
Aquatic biotope	4.79	0.426	4.17	0.753	2.50	0.527	3.90	1.155
Water vapor collection	4.00	0.784	4.67	0.516	3.90	0.738	4.10	0.759
Original site preservation	3.64	0.633	3.67	0.516	3.50	0.527	3.60	0.563
Topography usage	3.93	0.730	4.00	0.894	2.90	0.876	3.60	0.932
Walls	3.86	0.770	4.00	0.894	2.70	0.675	3.50	0.938
Rooftop garden/roof	4.36	0.745	4.50	0.548	4.00	0.667	4.27	0.691
Indoor garden/artificial forest	4.43	0.646	4.33	0.516	3.70	0.483	4.17	0.648
Vertical farm	4.50	0.519	4.33	0.516	4.30	0.675	4.40	0.563

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