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Integrating Streetscape Images, Machine Learning, and Space Syntax to Enhance Walkability: A Case Study of Seongbuk District, Seoul

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Abstract: As urbanization rapidly progresses, streets have transitioned from mere transportation corridors to crucial spaces for daily life and social interaction. While past research has examined the impact of physical street characteristics on walkability, there is still a lack of large-scale quantitative assessments. This study systematically evaluates street walkability in Seongbuk District, Seoul, through the integration of streetscape images, machine learning, and space syntax. The physical characteristics of streets were extracted and analyzed in conjunction with space syntax to assess street accessibility, leading to a combined analysis of walkability and accessibility. The results reveal that the central and western regions of Seongbuk District outperform the eastern regions in overall street performance. Additionally, the study identifies four distinct street types based on their spatial distribution: high accessibility–high overall score, high accessibility–low overall score, low accessibility–high overall score, and low accessibility–low overall score. The findings not only provide a scientific basis for street development in Seongbuk District but also offer valuable insights for assessing and enhancing walkability in cities globally.

Keywords: walkability; streetscape images; machine learning; space syntax; physical characteristics; Seongbuk District; Seoul

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1. Introduction

With the continued acceleration of urbanization, city streets have evolved from mere transportation corridors into vital spaces for residents' daily lives, social interactions, and physical activities [1]. Research has shown that high-quality pedestrian environments can significantly enhance residents' physical health and psychological well-being, reduce reliance on private vehicles, lower carbon emissions, and promote sustainable urban development [2,3]. Consequently, improving street walkability has become a primary objective in urban planning and design worldwide.

The analysis of physical street characteristics has long been a crucial entry point for studying the quality of pedestrian environments. Researchers widely acknowledge that physical features such as street width, building height, street furniture, vegetation, and building facades significantly impact pedestrian behavior. For instance, Li demonstrated that physical environmental factors, such as road geometry and surrounding conditions, significantly influence cyclists' comfort levels [4]. Similarly, Sung supported Jane Jacobs' assertion that urban vitality stems from physical diversity, finding a correlation between environmental diversity and pedestrian activity on Seoul's streets [5]. Additionally, Mahmoudi highlighted that issues such as improper sidewalk paving and inadequate maintenance reduce walkability on Kuala Lumpur's streets [6]. Finally, Abdul Rahman through exploratory factor analysis, underscored the importance of the physical street environment in creating pedestrian-friendly shopping streets in Malaysian urban settings [7]. However, despite these studies offering valuable insights and methods for analyzing street walkability through physical characteristics, previous research often required substantial time and effort, making large-scale quantitative analysis of pedestrian environments inefficient and costly.

In recent years, the rapid development of machine learning technologies and streetscape image data has allowed researchers to extract and analyze the physical characteristics of streets on a large scale. The application of these technologies enables more efficient acquisition of physical street information, which can be applied to walkability assessments. For example, Liu used streetscape images and machine learning techniques to evaluate elderly-friendly walking environments [8]. Kuo proposed a method for depicting and mapping building arcades using deep learning and streetscape images, offering a novel approach to analyzing the physical characteristics of urban street spaces [9]. Additionally, Wang explored the potential of using crowdsourced streetscape images to understand urban spatial vitality, focusing on inner-city London's walkability [10]. These studies illustrate that integrating streetscape images with machine learning has opened new avenues for researching the physical environment of streets, facilitating large-scale quantitative analysis of street walkability.

Simultaneously, space syntax has been widely employed as a tool for analyzing urban spatial structures, particularly in studies of street network accessibility [11]. Lerman utilized space syntax to model pedestrian movement in Bat Yam, Israel, predicting current and future pedestrian movement distribution [12]. Koohsari proposed a new walkability index based on space syntax and examined its relationship with pedestrian traffic [13]. Sharmin and Kamruzzaman explored the relationship between space syntax parameters and pedestrian movement, analyzing the variation in explanatory power across different parameters [14]. Nag used space syntax to assess the connectivity of three pedestrian networks in Varanasi, India, and investigated the relationships between pedestrian flow, space syntax parameters, and built environment characteristics [15]. However, despite significant advancements in urban accessibility studies using space syntax, its integration with streetscape images and machine learning for comprehensive street walkability evaluations remains relatively rare.

In this context, integrating streetscape images, machine learning, and space syntax to explore street walkability is highly valuable. Space syntax assesses street accessibility within the urban network, identifying streets that are more likely to be frequented by pedestrians. At the same time, streetscape-based physical quality analysis focuses on the pedestrian experience. Thus, combining streetscape images, machine learning, and space syntax allows for efficient evaluation of the physical quality of street spaces while precisely identifying high-accessibility streets (those more frequently used by pedestrians) and their walkability. This integration offers a robust decision-making foundation for more efficient street development.

Based on this framework, this study aims to systematically evaluate the walkability of streets in Seongbuk District, Seoul, by integrating streetscape images, machine learning, and space syntax. First, machine learning techniques (SegNet) are employed for semantic segmentation of streetscape images, calculating physical characteristic indicators of street space walkability. Then, the entropy weighting method is applied to comprehensively calculate the weights of these indicators, resulting in an overall walkability score for each street. Subsequently, space syntax is used to measure the accessibility of the street network, followed by a coupled analysis of overall walkability scores and accessibility results. Finally, recommendations are provided based on the analysis to enhance the walkability of streets within the study area.

2. Materials and Methods

This study systematically evaluates the walkability of streets in Seongbuk District, Seoul, by integrating streetscape images, machine learning, and space syntax (Figure 1). The research process is divided into the following steps:

(1) Street network data for the study area were collected from OpenStreetMap (OSM). The road network was then subjected to merging, simplification, and topological processing. Subsequently, street sampling points were generated along the streets.
(2) Google Street View images of Seongbuk District were collected using a Python (Python 3.11.0) script via the Google Street View API.
(3) The collected streetscape images were analyzed using a machine learning algorithm (SegNet) for semantic segmentation. This process extracted key visual elements of the streets (e.g., greenery, buildings, sky) and quantified their proportions in the images. The quantitative analysis of these visual elements provided foundational data for subsequent walkability assessments.
(4) Key indicators influencing walkability were identified based on previous research and literature reviews, including the Green Visual Index (GVI), Sky Visibility Index (SVI), and Street Facility Convenience Index (SFCI). The entropy weighting method was used to calculate the comprehensive weights of these indicators, which resulted in an overall walkability score for each street.
(5) The accessibility of the street network was assessed using space syntax.
(6) The overall walkability scores were combined with the accessibility results from the space syntax analysis.
(7) Based on the analysis results, recommendations were made to optimize the walkability of the streets in the study area.

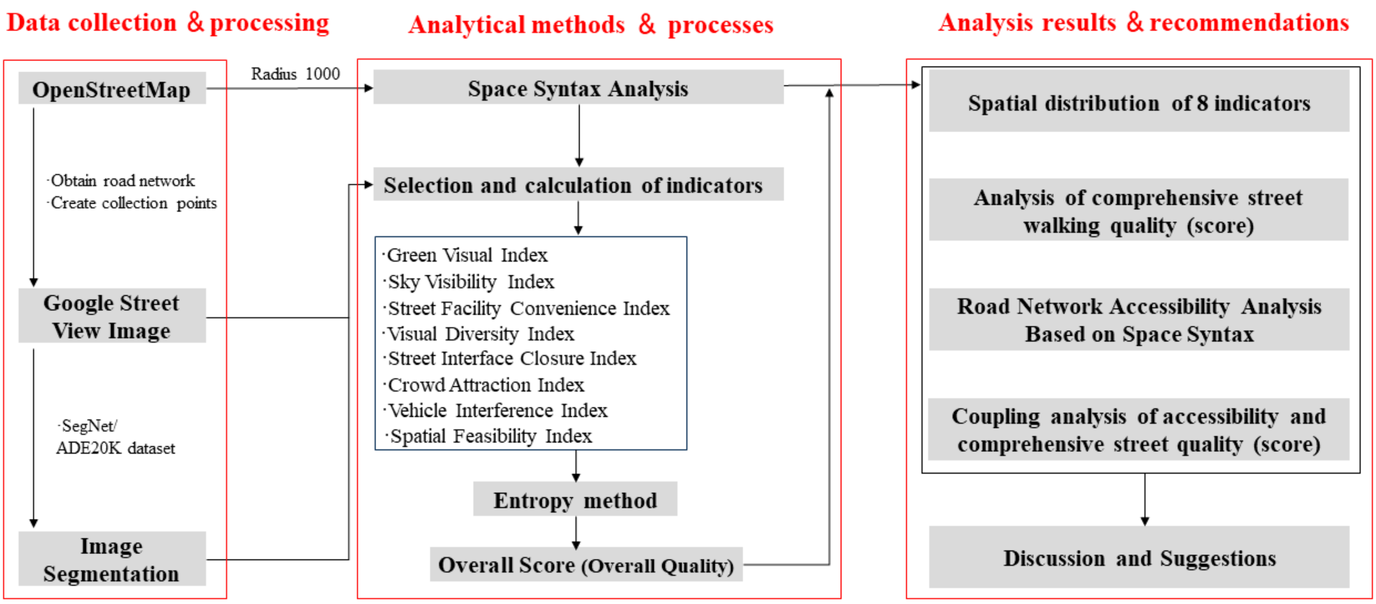

Figure 1. Research framework.

2.1. Study Area

This study focuses on Seongbuk District in Seoul, Republic of Korea (37°33′3.5″ N, 126°50′58.4″ E). Located in the northern part of Seoul, Seongbuk District spans approximately 24.57 square kilometers and has a resident population of about 460,000. The district comprises 20 administrative neighborhoods, including Jeongneung-dong, Donam-dong, Bomun-dong, and Anam-dong (Figure 2). Seongbuk District is renowned for its rich historical and cultural resources, as well as its educational institutions. It hosts several prestigious universities, such as Korea University, Sungkyunkwan University, and Kookmin University, forming a diverse and highly concentrated cultural and educational hub.

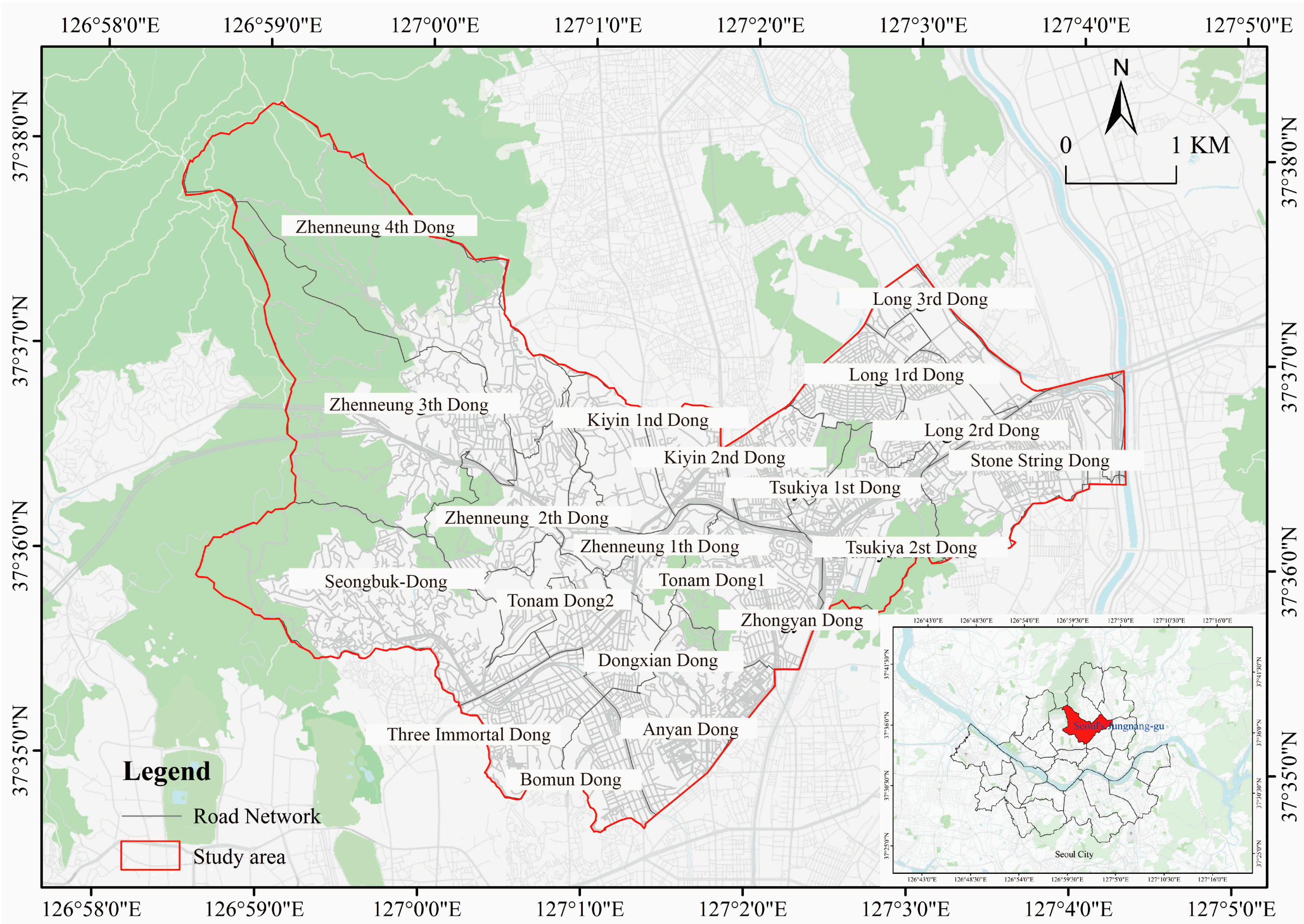

Figure 2. Study area.

The Seoul Metropolitan Government has explicitly set goals for improving street environment quality and enhancing pedestrian and bicycle networks in its "Seoul 2030 Urban Master Plan" and "Seoul 2040 Urban Plan" (https://urban.seoul.go.kr, accessed on 1 July 2024). These policies emphasize improving the physical street environment to enhance walkability, thereby boosting urban sustainability and livability. Additionally, Seoul has implemented the "Living Zone" initiative, which aims to improve the convenience of daily life and walking experiences for residents by optimizing public spaces and street environments [16]. As part of Seoul, Seongbuk District has gradually implemented and advanced street construction and walkability improvements in line with these overarching policies.

Thus, selecting Seongbuk District as the study area holds significant practical and research value. This study provides empirical evidence for street development in Seongbuk District and offers a reference for other cities seeking to conduct street walkability assessments in similar contexts.

2.2. Road Network Data and Google Street View Image (GSVI) Data

The road network data for this study were sourced from OpenStreetMap (http://www.openstreetmap.org, accessed on 3 July 2024). Streetscape image data were obtained from Google Maps, the world's largest online map service provider, which offers an API for accessing streetscape images. The data acquisition process was as follows: First, OSM road network data for the study area were collected and subjected to simplification, merging, road centerline extraction, and topological processing, resulting in 11,348 road segments. Next, in ArcGIS, sampling points were set at 100 m intervals along the road network, generating 6933 streetscape sampling points. Finally, Python and the Google Street View API were used to download streetscape images for the study area. Following previous studies [17], the horizontal field of view was set to 90°, and the pitch was set to 6°, ensuring a view equivalent to the pedestrian experience at eye level. For each streetscape sampling point, images were captured at four angles—0°, 90°, 180°, and 270°—and stitched into a 360° panoramic view. The maximum resolution was set to 640 × 640 pixels. Streetscape images with invalid access permissions were removed, resulting in a total of 5436 Google Street View images collected for the study area. The distribution of these images is shown in Figure 3.

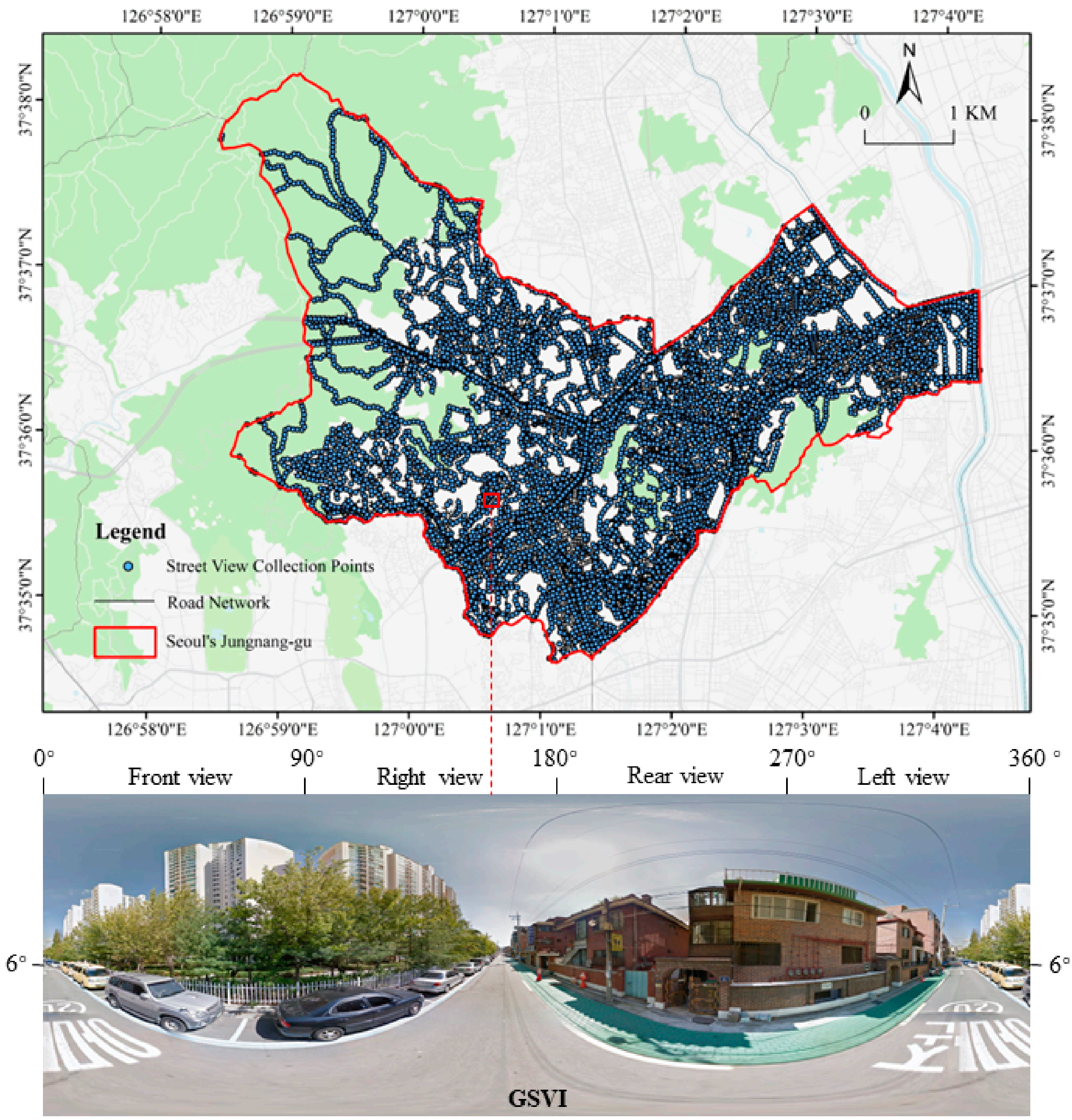

Figure 3. Google Street View image collection. The dots in the figure indicate the locations of the Street View images.

2.3. Semantic Segmentation of Images Using Machine Learning

To determine the proportions of various objects and elements within urban street spaces, this study utilized the SegNet model for semantic segmentation of streetscape images. SegNet is an open-source image segmentation model developed by a team at the University of Cambridge, capable of segmenting areas in images corresponding to objects such as cars, roads, and pedestrians with pixel-level precision [18]. Image segmentation is achieved through a convolutional neural network, which consists of two main parts: the encoder and the decoder. The encoder, based on the VGG16 network model, primarily parses object information. The decoder then maps this parsed information back into the final image form, where each pixel is assigned a color (or label) corresponding to its object information [19]. In essence, the encoder classifies and analyzes the low-level pixel values of the image to extract high-level semantic information (e.g., "car", "road", "pedestrian"), while the decoder assigns the corresponding pixels to each object, representing different objects with different colors [20].

Additionally, this study used the ADE20K dataset for training. ADE20K is an open-source semantic segmentation dataset released by the CSAILVision team at the Massachusetts Institute of Technology (MIT). The dataset includes 150 objects commonly found in daily life, such as vegetation, roads, sky, terrain, and traffic lights, and is widely used in scene understanding, parsing, segmentation, multi-object recognition, and semantic understanding. It is noteworthy that this study directly adopted a pre-trained model developed by Zhao et al., which achieved an accuracy of up to 80.13% [21,22]. Therefore, using this dataset for semantic segmentation provides reliable data for the subsequent quantification of physical indicators of street walkability.

2.4. Development of the Street Walkability Indicator System and Calculation of Comprehensive Walkability

This study utilized frequency analysis to statistically examine existing research on urban street walkability. Initially, 20 evaluation indicators from previous studies were selected for analysis [23–28]. Based on the measurable content derived from machine learning applied to streetscape images, eight indicators were identified across three dimensions: walkability comfort, walkability attractiveness, and walkability safety. These indicators include the Green Visual Index (GVI), Sky Visibility Index (SVI), Street Facility Convenience Index (SFCI), Street Interface Closure Index (SICI), Crowd Attraction Index (CAI), Vehicle Interference Index (VII), and Spatial Feasibility Index (SFI) (Table 1).

Furthermore, considering the advantages of the entropy method in determining weight coefficients based on the degree of variation among indicators, without the influence of subjective factors [29], this study used the entropy method to calculate the comprehensive weights of the walkability indicators. This approach allowed for the determination of a comprehensive walkability score for street spaces within the study area. The calculation process is briefly outlined as follows: First, the extreme value method was used to standardize each indicator. Next, the proportion P_{ij} of the i-th evaluation object under the j-th indicator was calculated. Then, the information entropy E_j for the j-th indicator was derived based on the proportion, leading to the determination of the weight W_j for each indicator. Finally, by integrating the standardized values of each indicator with their respective weights, the comprehensive evaluation index was calculated (Table 2).

Table 1. Eight evaluation indicators of street walking quality are constructed from three dimensions.

Primary Dimension	Secondary Indicators	Formulas	Street View Image Segmentation Labels	Metric Attributes
Walking comfort	Green Visual Index (GVI)	$GVI = \frac{Gn}{An}$	Gn is the number of vegetation pixels in the n-th image; An is the total number of pixels in the n-th image.	Positive
	Sky Visibility Index (SVI)	$SVI = \frac{Vn}{An}$	Vn is the number of sky pixels in the n-th image; An is the total number of pixels in the n-th image.	Positive
	Street Facility Convenience Index (SFCI)	$SFCI = \frac{\sum f_j}{An}$	$\sum f_j$ is the sum of pixels for street facilities (streetlights, benches, signage) in the image; An is the total number of pixels in the n-th image.	Positive
Walking attraction	Visual Diversity Index (VDI)	$VDI = \frac{\sum D_i}{An}$	$\sum D_i$ is the sum of all elements in the street image; An is the total number of pixels in the n-th image.	Positive
	Street Interface Closure Index (SICI)	$SICI = \frac{In}{An}$	In is the sum of pixels for enclosures (walls, fences) in the street image; An is the total number of pixels in the n-th image.	Negative
	Crowd Attraction Index (CAI)	$\text{CAI} = \frac{Pn}{An}$	Pn is the number of pedestrian pixels in the n-th image; An is the total number of pixels in the n-th image.	Positive
Walking safety	Vehicle Interference Index (VII)	$\text{VII} = \frac{Vn}{A_n}$	Vn is the number of vehicle pixels (cars, buses, trucks) in the n-th image; An is the total number of pixels in the n-th image.	Negative
	Spatial Feasibility Index (SFI)	$\text{SFI} = \frac{Fn}{A_n}$	Fn is the number of pixels representing pedestrian spaces (sidewalks, paths, trails) and roadways in the n-th image; An is the total number of pixels in the n-th image.	Positive

Table 2. Weights of street walking quality index system based on the entropy method.

Goal Layer	Criterion Layer	Weight	Indicator Layer	Weight
Street walkability assessment	Walking comfort	0.560	Green Visual Index (GVI)	0.196
			Sky Visibility Index (SVI)	0.021
			Street Facility Convenience Index (SFCI)	0.344
	Walking attraction	0.434	Visual Diversity Index (VDI)	0.003
			Street Interface Closure Index (SICI)	0.018
			Crowd Attraction Index (CAI)	0.413
	Walking safety	0.006	Vehicle Interference Index (VII)	0.003
			Spatial Feasibility Index (SFI)	0.003

2.5. Calculation of Road Network Accessibility Using Space Syntax

The topological properties and spatial distribution of urban streets are key determinants of the walkability potential and accessibility of a city's street network [30]. Space syntax, developed in the early 1980s by University College London, is a research method that analyzes the relationship between spatial networks and social activities [31]. Its strength lies in quantifying urban space accessibility by establishing topological relationships between points and lines, particularly for street accessibility [32]. In space syntax, accessibility is quantified by the Integration value, where a higher value indicates greater accessibility, meaning the street is more easily traversed by residents and experiences higher pedestrian traffic [33]. Space syntax theory also introduces three classic spatial segmentation models: convex maps, visibility graph analysis (VGA), and segment maps. Currently, the segment map model, which accounts for both angular deviation and metric distance in the street network, has become the mainstream approach in urban space accessibility research. This model more accurately reflects changes in spatial configuration due to geometric transformations, aligning more closely with actual wayfinding behavior [34].

In recent years, with the shift in urban planning concepts, particularly the proposal and promotion of the "15-Minute City" concept, the importance of space syntax in assessing walkability has become increasingly prominent. The "15-Minute City" emphasizes that residents should be able to access various daily facilities within 15 min, based on the principles of time geography and behavioral geography, highlighting the close relationship between spatial accessibility and daily activity patterns [35]. In line with the "15-Minute City" concept, especially within the context of Seoul's gradual establishment of 15 min walking circles, this study set a 1000 m radius for walkability assessments [36], ensuring alignment between the evaluation of street networks and urban planning objectives.

The specific process is as follows: First, the road network data were merged, simplified, and topologically processed in ArcGIS. Then, the processed network was imported into the space syntax software "Depthmap" (Depthmap+ Beta 1.0 2012)for calculating integration (accessibility) within a 1000 m radius. Finally, in ArcGIS, a coupling analysis was conducted between the top 20% and bottom 20% of streets in terms of accessibility and overall street walkability scores.

3. Results

3.1. Spatial Distribution of Eight Indicators

The study results reveal the following spatial distribution characteristics of the eight indicators (Figure 4, Table 3):

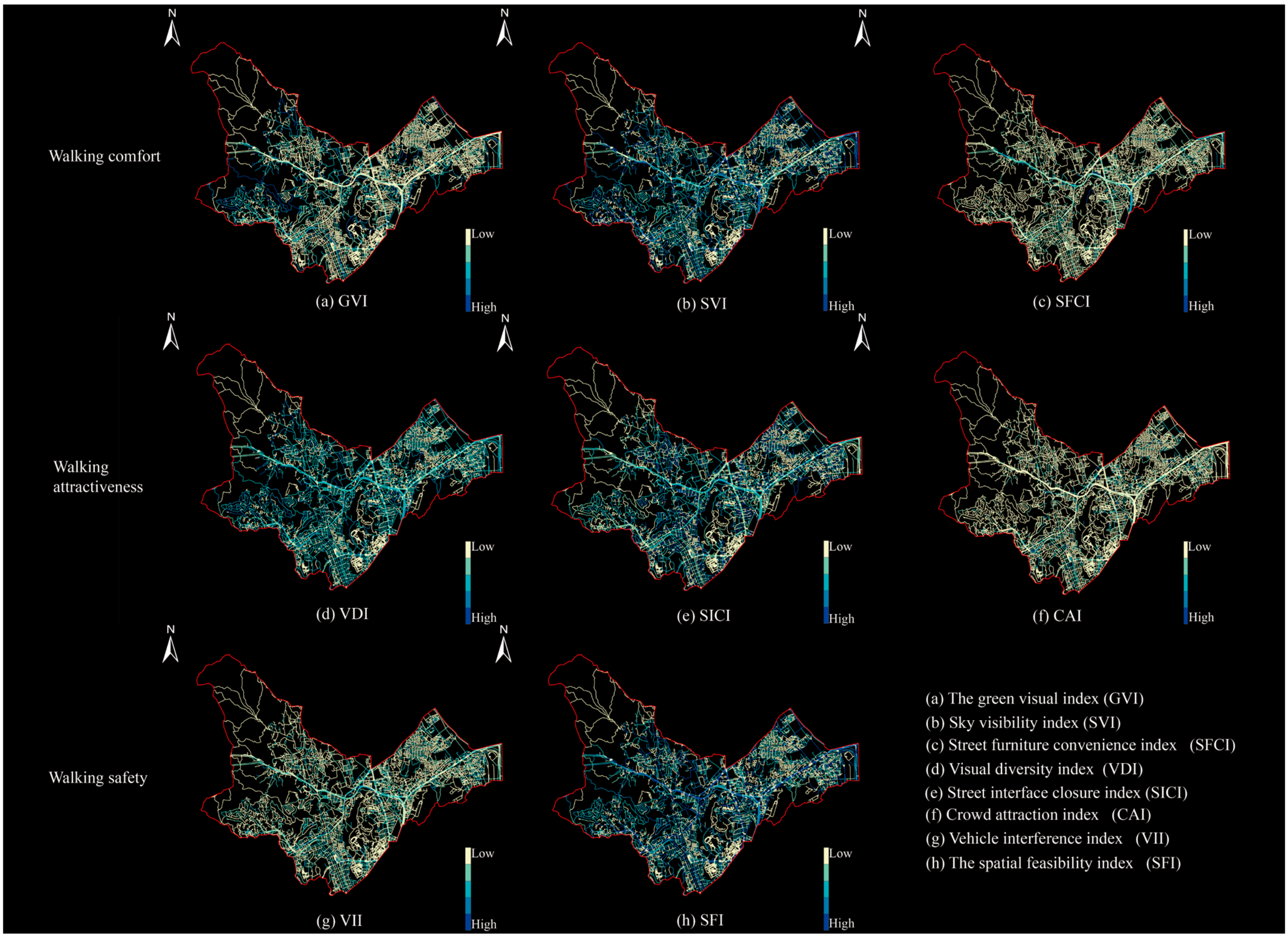

Figure 4. Spatial distribution of the eight indicators.

Table 3. Statistical analysis of the characteristics of the eight indicators.

Type	Average	Max	Min	S.D
GVI	0.070	0.545	0.000	0.081
SVI	0.292	0.474	0.000	0.089
SFCI	0.007	0.264	0.000	0.016
VDI	0.991	1.513	0.000	0.100
SICI	0.192	0.496	0.000	0.095
CAI	0.001	0.032	0.000	0.002
VII	0.020	0.251	0.000	0.026
SFI	0.386	0.480	0.000	0.051

First, the average Green Visual Index (GVI) is 0.070, significantly below the international benchmark of 25% for a good GVI [37], suggesting a relatively low level of greenery in the study area. Certain areas, however, exhibit a high GVI value of up to 0.545, indicating a good level of greening. The standard deviation (S.D. = 0.081) reveals considerable variation in GVI across different regions, highlighting an uneven distribution of greenery. Areas with higher GVI values are concentrated in Seongbuk-dong, Jeongneung 3rd dong, and Jeongneung 2nd dong. In comparison, the average Sky Visibility Index (SVI) is 0.292, with a standard deviation of 0.089, indicating some variation in sky visibility across different areas, though the distribution is more balanced compared to GVI. Higher SVI values are found along major roads, whereas densely built-up residential streets have more restricted sky visibility. The average Street Facility Convenience Index (SFCI) is 0.007, with a standard deviation of 0.016, reflecting generally poor street facility convenience across most areas. Only a few regions (maximum value of 0.264) have well-equipped street facilities. These facilities are primarily concentrated around transportation hubs such as the Northern Arterial Road, the Internal Loop Road, and areas near Songcheon Road. In contrast, on urban secondary roads and community streets, facility convenience is low, indicating an imbalance in the distribution of facilities.

Secondly, the Visual Diversity Index (VDI) has an average value of 0.991 and a standard deviation of 0.100, indicating significant differences in visual diversity across Seongbuk District, with a maximum value of 1.513. Major streets exhibit richer visual elements, while residential areas and secondary streets show lower visual diversity, closely related to the allocation of street facilities and road hierarchy. The average Street Interface Closure Index (SICI) is 0.192, with a standard deviation of 0.095 and a maximum value of 0.496, indicating that some areas have relatively closed street spaces. This is particularly evident in narrow community-level streets, where buildings and fences limit street openness. The Crowd Attraction Index (CAI) has an extremely low average value of 0.001 and a standard deviation of 0.002, indicating that most streets experience low pedestrian traffic. Walking activities are more active only near a few commercial and community streets (maximum value of 0.032).

Lastly, the Vehicle Interference Index (VII) has an average value of 0.020 and a standard deviation of 0.026, indicating that major arterial roads experience higher motor vehicle traffic, posing greater interference to pedestrians, whereas secondary streets have less vehicle interference. The Spatial Feasibility Index (SFI) has an average value of 0.386 and a standard deviation of 0.051, suggesting that streets in Seongbuk District generally have ample walking space, with a relatively even distribution across different areas.

3.2. Analysis of Comprehensive Street Walkability

Using the previously mentioned entropy method, we calculated the weights of the eight indicators and derived the comprehensive scores for these indicators. Subsequently, a distribution map and a heatmap of comprehensive street quality in the study area were generated. The distribution map of comprehensive street quality (Figure 5) reveals significant variations in street walkability across different regions within Seongbuk District. The colors on the map represent the comprehensive quality scores of the streets: darker colors (approaching blue) indicate higher walkability scores, while lighter colors (approaching yellow) indicate lower scores.

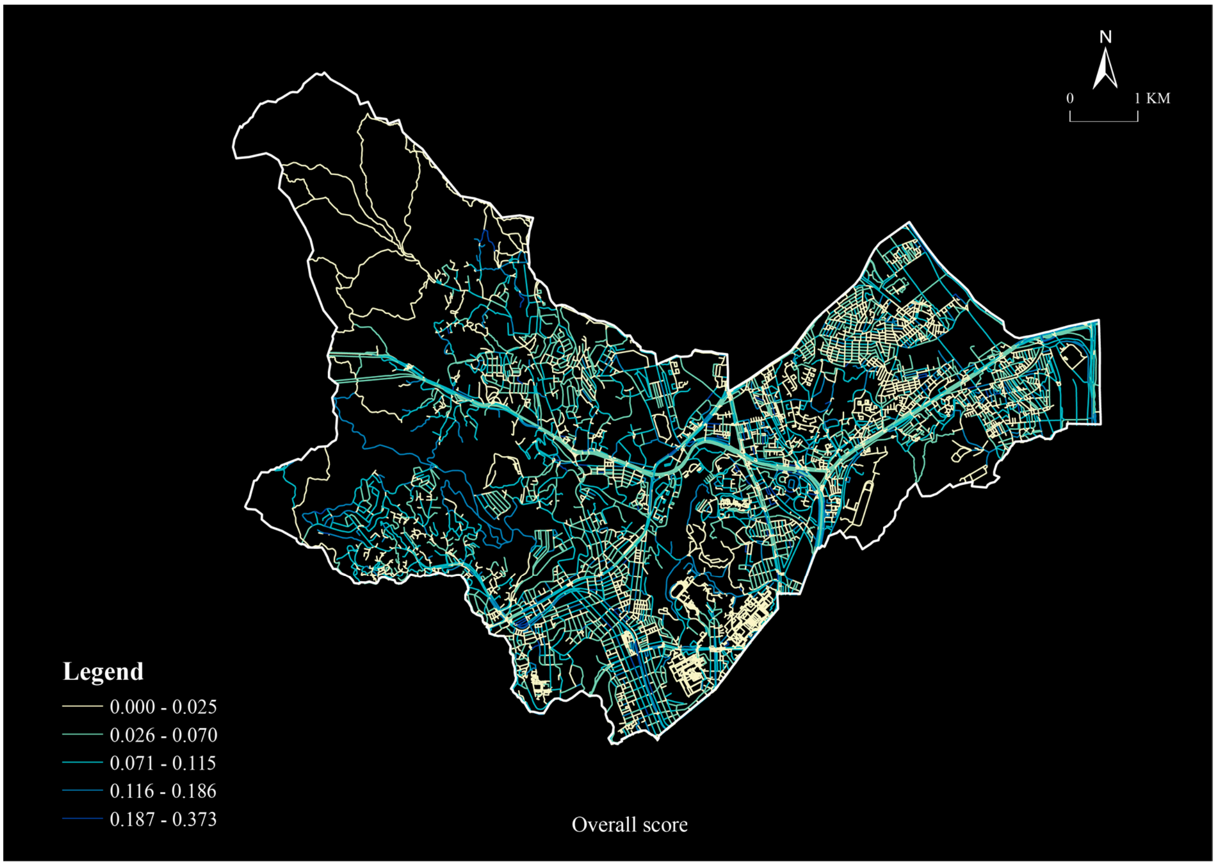

Figure 5. Comprehensive quality distribution map of the street.

Streets with higher comprehensive scores are mainly located near ecological resources, such as parks, rivers, and forests, including streets like Hwarang-ro, Bomun-ro, and Bugaksan-ro, as well as major thoroughfares like the Northern Arterial Road, the Internal Loop Road, and Dongsomun-ro. In contrast, areas with lower scores are mostly found on the urban periphery and some community-level streets.

The heatmap of comprehensive quality (Figure 6) shows that hotspots are primarily concentrated in regions such as Seongbuk-dong, Jeongneung 3rd dong, Gireum 1st dong, Jeongneung 1st dong, and the eastern part of Seokgwan-dong. In contrast, cold spots are concentrated in areas like Anam-dong, Jangwi 2nd dong, and the southern part of Samseon-dong. Overall, the central and western regions of Seongbuk District exhibit higher street walkability compared to the eastern regions.

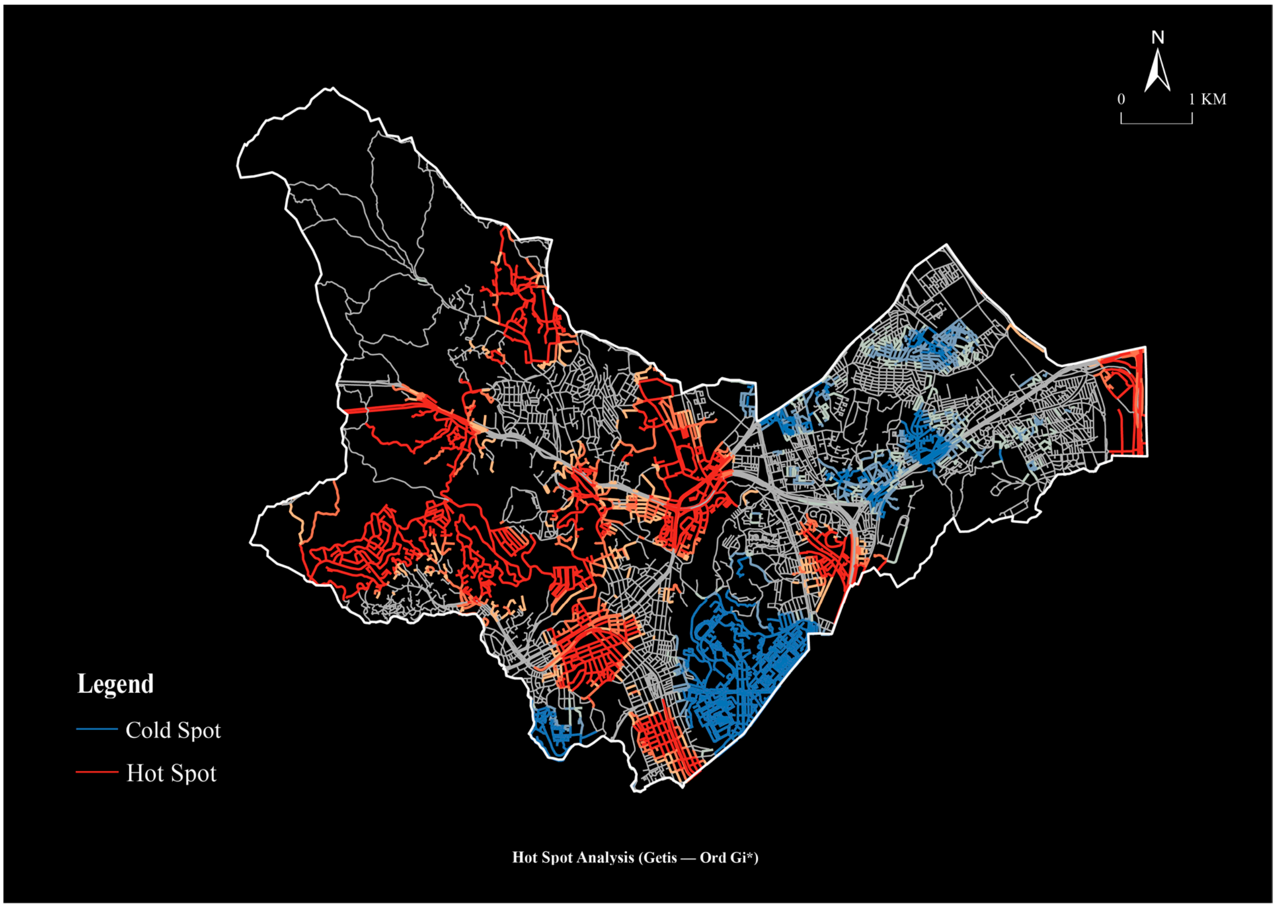

Figure 6. Comprehensive quality heat map.

3.3. Road Network Accessibility Analysis Using Space Syntax

Figure 7 shows the distribution of road network accessibility in Seongbuk District, as analyzed using space syntax. The colors in the figure range from blue to red, representing street accessibility scores from low to high, respectively. Streets with higher accessibility are primarily located in areas such as Jangwi 1st dong, Seokgwan-dong, Hawolgok 1st dong, and Dongseon-dong. These streets are aligned with major urban arterial roads, such as the Northern Arterial Road, the Internal Loop Road, Dongsomun-ro, and Jongam-ro, indicating strong connectivity within the urban transportation network and potentially higher pedestrian traffic.

In contrast, streets with lower accessibility are primarily distributed in the western and northern parts of Seongbuk District. These streets are often situated far from major arterial roads and are influenced by the natural environment, resulting in a sparser road network.

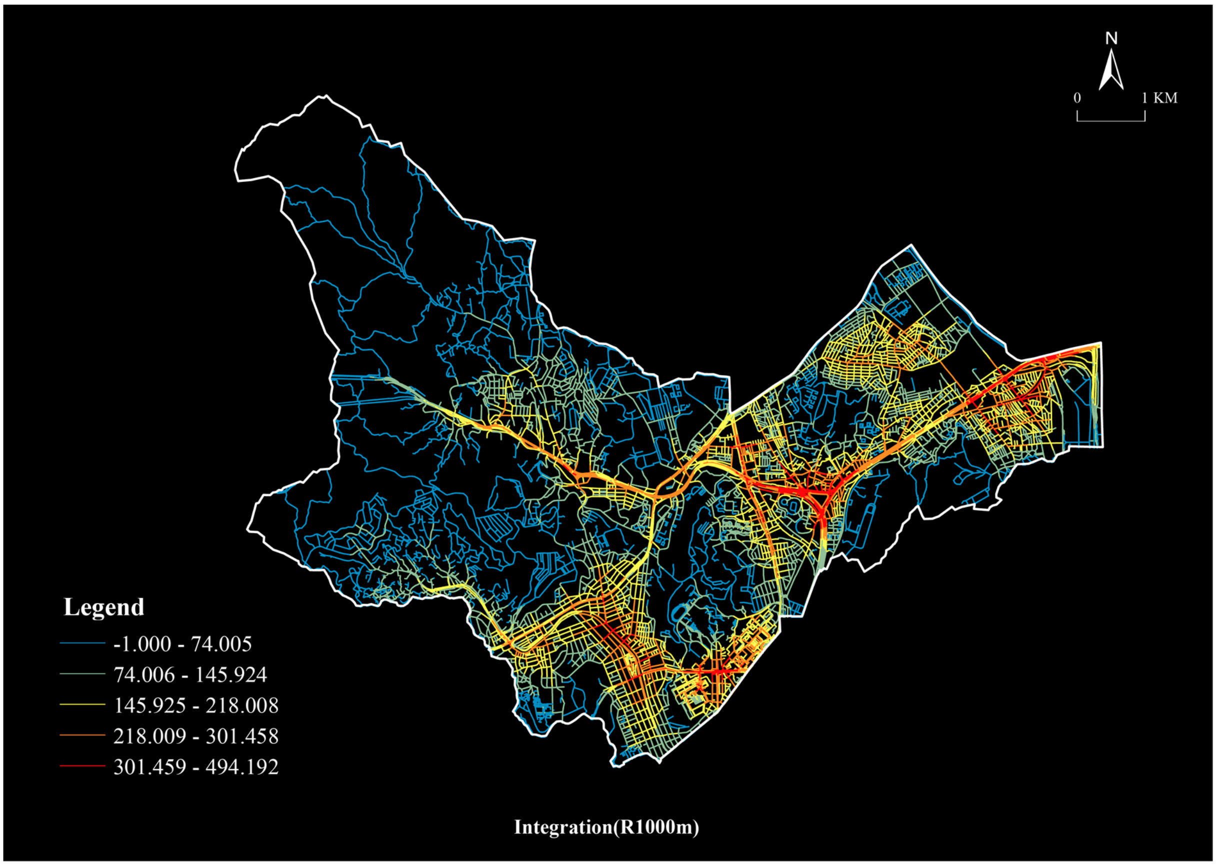

Figure 7. Street accessibility distribution in the study area (R1000).

3.4. Coupling Analysis of Accessibility and Comprehensive Street Quality

Figure 8 presents the results of the coupling analysis between street accessibility and comprehensive quality scores in Seongbuk District, categorizing the streets into four types: (a) high accessibility–high overall score, (b) high accessibility–low overall score, (c) low accessibility–high overall score, and (d) low accessibility–low overall score. Figure 9 provides representative streetscape images illustrating the actual environmental conditions of each street type.

First, streets marked in purple in Figure 8a exhibit both high accessibility and high comprehensive quality scores. These streets are mainly located near major traffic arteries such as the Northern Arterial Road, the Internal Loop Road, Dongsomun-ro, and Jongam-ro. The representative streetscape images in Figure 9a show that these streets feature good greenery coverage and well-developed pedestrian facilities, offering a comfortable walking environment. These areas demonstrate significant advantages in both walkability and accessibility.

Second, streets marked in red in Figure 8b, although situated near major traffic arteries and thus having high accessibility, show lower comprehensive quality scores due to poor walking environment quality. These streets often suffer from insufficient greenery and a lack of street facilities, leading to a subpar pedestrian experience. The representative streetscape images in Figure 9b depict these areas as relatively monotonous, with a lack of pedestrian facilities, indicating that high accessibility does not necessarily translate to high-quality walkable streets.

Additionally, streets marked in yellow in Figure 8c are located in areas such as Seongbuk-dong, Donam 2nd dong, and Donam 1st dong. Despite their lower accessibility, these streets boast a good natural environment and well-maintained street facilities, resulting in high comprehensive quality scores. The representative streetscape images in

Figure 9c show that these streets are rich in greenery, have ample walking space, and are equipped with numerous street amenities.

Finally, streets marked in blue in Figure 8d are primarily located in the Jeongneung 4th dong area. These streets lack both traffic accessibility and a favorable walking environment, leading to low comprehensive quality scores. The representative streetscape images in Figure 9d illustrate these streets as poorly equipped, with deteriorated environments and inadequate walking conditions.

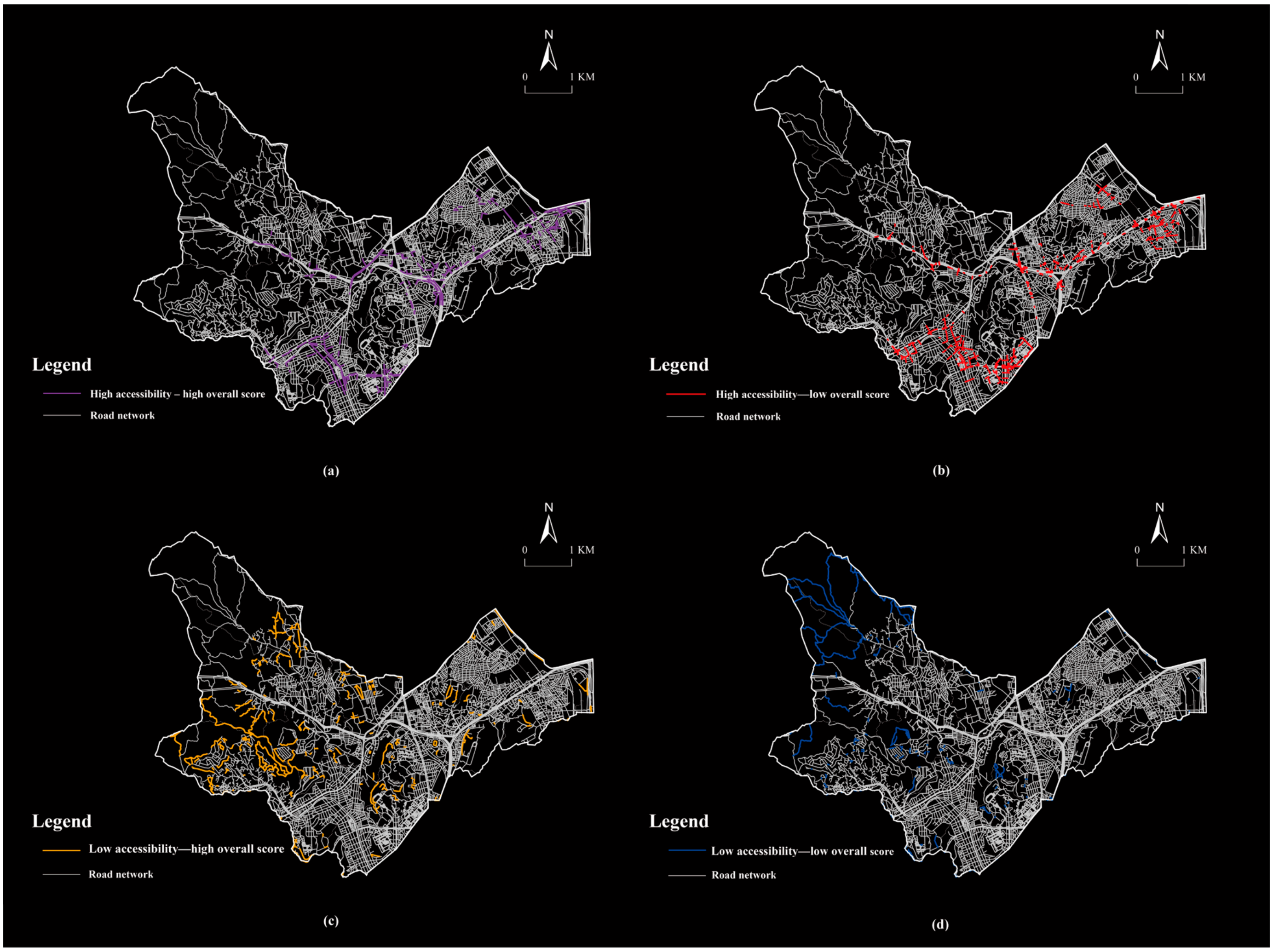

Figure 8. Coupling analysis of street accessibility and walkability evaluation. (**a**) High accessibility–high overall score. (**b**) High accessibility–low overall score. (**c**) Low accessibility–high overall score. (**d**) Low accessibility–low overall score.

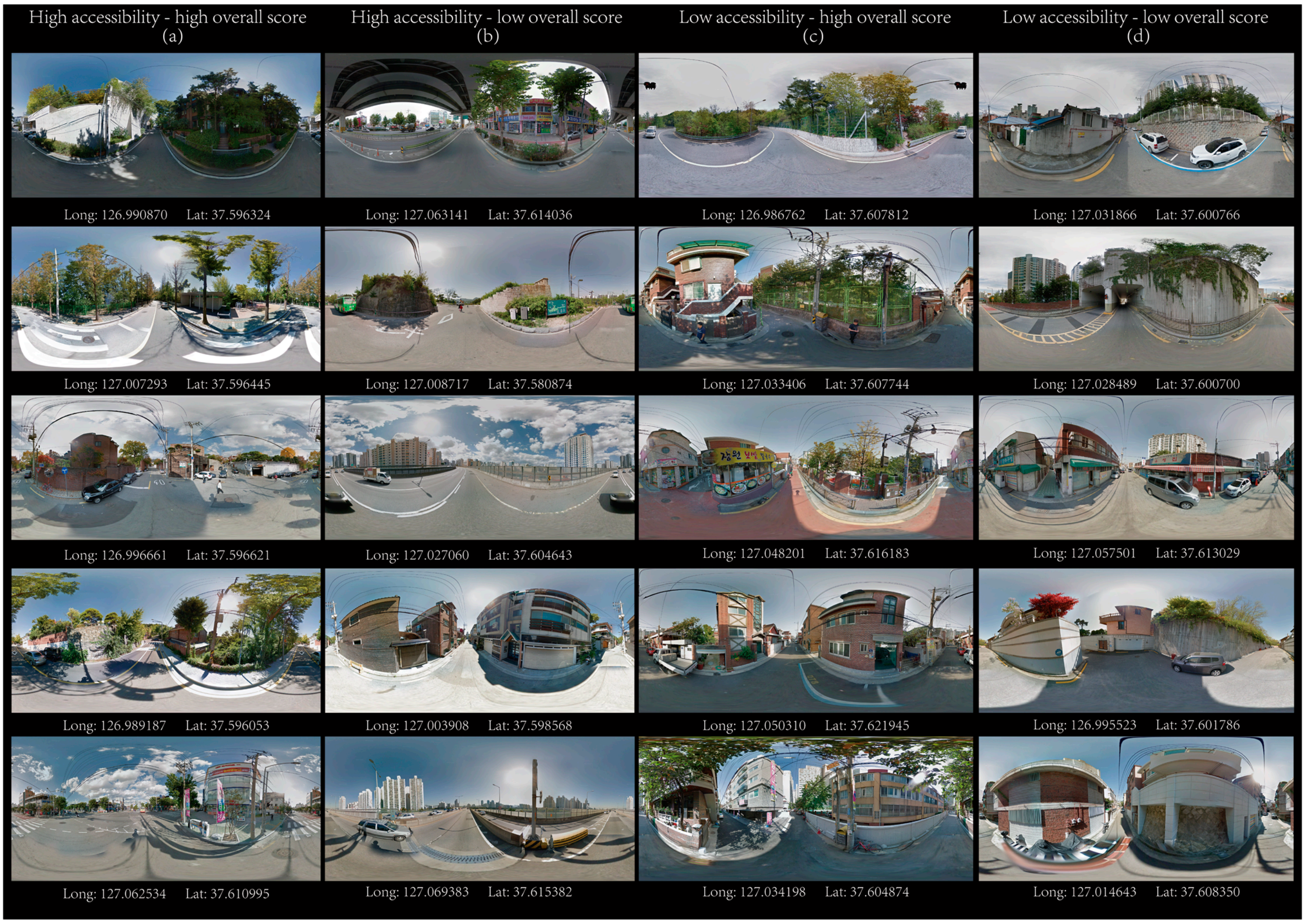

Figure 9. Representative Street View imagery for four coupling types.

4. Discussion

4.1. General Discussion

This study, in response to the increasing demands for improved walkability amid urbanization, proposes a novel approach that integrates streetscape images, machine learning, and space syntax to systematically assess the walkability of streets in Seongbuk District, Seoul. As urban demand for walkability grows, enhancing the walking environment has become a key objective in global urban planning. However, existing studies are often confined to localized areas or rely solely on traditional survey methods, which lack large-scale, systematic quantitative analysis tools.

This study introduces significant methodological advancements. Compared to traditional walkability studies [38,39], this research incorporates streetscape images and machine learning techniques, enabling the efficient acquisition and analysis of physical street characteristics across a broad area. Additionally, by integrating space syntax analysis, this study comprehensively evaluates the relationship between street network accessibility and walkability. This approach not only enhances data processing efficiency and accuracy but also addresses the limitations of previous studies in large-scale quantitative analysis. Moreover, the proposed method enables a holistic evaluation of street accessibility and overall quality. For instance, identifying streets with high accessibility but low walkability quality can help urban managers pinpoint potential problem areas. This dual analytical capability provides urban managers with specific action guidelines, ensuring precise resource allocation and promoting balanced and optimized street development.

In terms of indicator selection, this study employs several key metrics, including the Green Visual Index (GVI), Sky Visibility Index (SVI), and Street Facility Convenience Index (SFCI), which collectively reflect the comfort, attractiveness, and safety of the street walkability environment. Additionally, by calculating the comprehensive weights of these indicators using the entropy method, the study ensures the objectivity and reliability of the assessment results.

Compared to existing studies [40–42], this research makes significant contributions in two key areas: first, by integrating streetscape images with machine learning techniques, it achieves a large-scale, precise assessment of walkability; second, by coupling walkability quality with space syntax analysis, it reveals the complex relationship between street accessibility and walkability quality. This research not only provides a scientific basis for street optimization in Seongbuk District, Seoul, but also offers robust support for walkability assessment and improvement in other cities.

Notably, cities worldwide are gradually transitioning from vehicle-oriented to pedestrian-friendly environments. Koh highlighted that Seoul, through a series of pedestrian-prioritized policy measures—such as the creation of pedestrian-only streets, the restoration of public spaces, and the improvement of pedestrian infrastructure—has effectively enhanced the quality of the walking environment and overall urban livability [43]. This real-world example demonstrates the crucial role of policy intervention in promoting walkability and offers valuable lessons for other cities. These measures align with the innovative approaches of this study, suggesting that the combination of policy guidance and scientific evaluation tools can further optimize urban walking environments and improve residents' quality of life.

4.2. Analysis of Research Findings

(1) The eight indicators of street walkability in Seongbuk District, Seoul, show significant regional variations. GVI (Green Visual Index) and CAI (Crowd Attraction Index) levels are closely linked to the distribution of natural resources within the area. Regions near parks, rivers, forests, and schools tend to have higher GVI scores and attract more pedestrian traffic. In contrast, the city center and densely built areas, where space is limited, show lower and more unevenly distributed greenery. The distribution of SFCI (Street Facility Convenience Index) may correlate with the presence of transportation hubs and commercial activities, where facilities are more developed. However, community streets and urban peripheries suffer from relatively poor facility convenience due to less resource investment. The variation in VDI (Visual Diversity Index) primarily reflects the visual diversity of physical infrastructure in street spaces, likely associated with wider streets and better-equipped facilities on urban arterial roads. Conversely, community-level streets, characterized by dense buildings and limited space, exhibit lower visual diversity and higher SICI (Street Interface Closure Index), indicating more enclosed spaces. VII (Vehicle Interference Index) and SVI (Sky Visibility Index) score higher on major roads, likely due to increased vehicle traffic and broader roadways. Lastly, the overall good performance of SFI (Spatial Feasibility Index) within the study area may be attributed to the continuous and well-paved street interfaces in Seongbuk District.

(2) The central and western regions of Seongbuk District exhibit higher comprehensive street walkability compared to the eastern region. This disparity may be due to the central and western regions' abundance of natural resources (e.g., Bukhansan), superior transportation, multi-centered commercial hubs, and the presence of several universities (e.g., Kookmin University, Korea University, Sungshin Women's University, and Seokyeong University). These factors likely enhance the walkability environment in these areas.

(3) Streets near the main urban arterial roads in Seongbuk District have higher accessibility, while those in the western and northern regions show lower accessibility. This is closely related to the geographical features and urban development patterns of the study area. The relatively flat terrain in the central and eastern regions facilitates large-scale urban development and road network construction. The concentration of residential and com-

mercial zones in these areas results in a dense road network with strong street connectivity, leading to higher accessibility in space syntax analysis. Conversely, lower accessibility in the western and northern regions may be due to geographical barriers such as mountains and hills, which limit the extension and interweaving of roads, resulting in a sparser and more winding road network, and consequently lower accessibility in space syntax analysis.

(4) There is a significant discrepancy between street walkability quality and accessibility in Seongbuk District, with some streets exhibiting low walkability quality despite high accessibility, and vice versa. This discrepancy may be related to uneven urban planning and resource allocation across different regions. Streets with high accessibility but low walkability quality might be overly focused on transportation functions, neglecting the development of a walkable environment, leading to deficiencies in greenery and facilities. Conversely, streets with low accessibility but high walkability quality might be located in quieter residential areas or near natural resources, where, despite poorer traffic connectivity, the pleasant environment and well-maintained pedestrian facilities contribute to a higher overall quality.

4.3. Implications and Recommendations

To further enhance street walkability in the study area, based on the findings and analysis results, we propose the following recommendations:

(1) Enhancing ecological resources in the eastern region: The government should intensify efforts to develop ecological resources in the eastern region, such as increasing the number of parks, green spaces, and riverside walkways, to improve the Green Visual Index (GVI) and Crowd Attraction Index (CAI) in this area. These measures would not only enhance the aesthetic quality of the environment but also increase walkability, especially in areas with relatively low greenery levels. By raising GVI and CAI, the area can effectively promote pedestrian activity and improve overall street walkability.

(2) Improving public transportation and commercial layout: By enhancing the public transportation network and optimizing commercial layouts in the eastern region, the government can increase traffic convenience and commercial vitality, thereby attracting more pedestrian traffic and enhancing street walkability. For streets with high accessibility but low walkability, priority should be given to improving walking comfort (e.g., increasing the Sky Visibility Index, SVI), enhancing street facility convenience (SFCI), and redesigning street layouts to optimize the Visual Diversity Index (VDI). These measures will help balance the needs of transportation functionality with the requirements of a walkable environment, ensuring that these streets offer both convenient access and a comfortable pedestrian experience.

(3) In high accessibility and high walkability streets, the government can invest more resources to improve pedestrian infrastructure, such as widening sidewalks, adding benches along walkways, installing lighting, and enhancing signage systems to increase pedestrian comfort and safety. Maintaining the existing high levels of Green Visual Index (GVI) and pedestrian safety indicators, such as the Vehicle Interference Index (VII), is essential. These measures will help these streets sustain their walking advantages within the area and further enhance the overall quality of the walking environment [44].

(4) Redesigning streets with high accessibility but low walkability: For streets that exhibit high accessibility but low walkability, it is recommended to reassess their design, adding green belts, optimizing sidewalk paving, reducing the width of motor vehicle lanes, and increasing pedestrian crossing facilities to improve walkability. By enhancing the Sky Visibility Index (SVI) and Green Visual Index (GVI) while optimizing the Street Facility Convenience Index (SFCI), the walkability of these streets can be significantly improved, allowing them to fully leverage their high accessibility to attract more pedestrians.

(5) Enhancing connectivity for streets with low accessibility but high walkability: For streets with low accessibility but high walkability, such as those in Seongbuk-dong, it is recommended to maintain the environmental advantages of these streets while increasing their connectivity to the public transportation system. This approach will not only allow

the walkability advantages of these areas to be more widely utilized but also enhance the overall attractiveness of these streets by improving the Street Interface Closure Index (SICI) and Crowd Attraction Index (CAI), making them more vibrant and appealing walking and living spaces.

(6) Comprehensive environmental improvements for streets with low accessibility and low walkability: For streets that exhibit both low accessibility and low walkability, it is suggested to implement comprehensive environmental improvement measures. Infrastructure investments can enhance the Spatial Feasibility Index (SFI) of walking spaces, while adding public transportation routes can gradually improve the accessibility of these areas. Additionally, ecological restoration and overall improvements to the walking environment can help narrow the gap in street walkability between these areas and other regions.

In summary, this study recommends that urban planning adopt a differentiated strategy, setting different priorities for improvement based on the distinct characteristics of each street type. By rationally allocating resources and optimizing key indicators such as the Street Facility Convenience Index (SFCI) and Sky Visibility Index (SVI), it is possible to ensure that all types of streets receive appropriate development and improvements, thereby enhancing the overall walkability of urban streets.

Moreover, enhancing the walkability of urban environments not only relies on the improvement of physical infrastructure but also requires the effective use of cultural and community resources. Community engagement and cultural activities can significantly enhance the vibrancy and attractiveness of street spaces. The regeneration experience in Seongbuk-dong, Seoul, demonstrates that deep collaboration between artists and community organizations can unlock the cultural potential of the area, increasing the public use of street spaces. This culture-driven urban regeneration model has not only improved the aesthetic quality of walkable spaces but also strengthened community cohesion and participation, thereby positively impacting the walking environment [45].

4.4. Limitations and Future Research Directions

This study has several limitations. First, although a substantial amount of streetscape image data was used, the timeliness and update frequency of this data could impact the accuracy of the results. In rapidly developing urban environments, the lag in streetscape image data may lead to discrepancies between the analysis outcomes and current actual conditions. Future research could consider integrating real-time updated streetscape data and combining it with multi-source data, such as satellite imagery and drone footage, to provide a more comprehensive and dynamic assessment of urban walkability.

Second, walking behavior is influenced by a complex array of factors, including sociocultural background, individual psychological states, and weather conditions, which were not fully incorporated into this study's analysis. Therefore, while this study provides a detailed analysis at the physical spatial level, it is somewhat limited in capturing the diversity and complexity of walking behavior. Future research could integrate individual needs and community characteristics to propose more personalized street walkability improvement strategies. For example, through refined analysis, strategies could be developed to enhance street walkability for different population groups (e.g., the elderly, children, and people with disabilities), ensuring sustainable and inclusive urban development.

Furthermore, future research should explore the potential applications of smart cities and smart districts in enhancing walkable environments. For example, the Smart District project in Špitálka, Brno, has successfully improved the accessibility and convenience of walkable environments through smart sensing technologies and data-driven urban management [46]. The application of these smart technologies can address issues such as outdated data and the exclusion of diverse factors in walkability optimization, providing more precise and real-time guidance for street design and functional improvements. This practical experience suggests that future research should consider integrating the concept of smart districts into the evaluation and enhancement of street walkability, leveraging intelligent approaches to achieve more dynamic and personalized walkability optimization strategies.

Additionally, Pawlusinski's study on Krakow's night-time economy highlights that the development of the night-time economy presents specific infrastructure needs and poses challenges to sustainable urban management [47]. To further improve the quality of the night-time walking environment, future research should consider factors such as night-time lighting, safety, and the optimization of public transportation during night hours. These measures can enhance the night-time walking experience and support the growth of the night-time economy, achieving a dual improvement in walkability and urban vibrancy. This also suggests that future walkability studies should pay closer attention to walking behaviors at different times of the day and their implications for urban planning to achieve a more comprehensive and dynamic optimization of walking environments.

5. Conclusions

In this study, we successfully integrated streetscape images, machine learning, and space syntax to develop a comprehensive street walkability assessment framework, applied in Seongbuk District, Seoul. This approach enabled us to perform a quantitative analysis of both the physical characteristics and accessibility of streets, accurately identifying the relationship between walkability quality and street accessibility, thereby providing a scientific basis for urban planning and street optimization.

The findings revealed significant differences in the comprehensive walkability quality of streets across Seongbuk District, with the central and western regions performing better, while the eastern region exhibited relatively lower walkability quality.

Finally, we encourage future urban planning efforts to adopt the methods used in this study, integrating real-time data and personalized needs, to further enhance street walkability and promote urban sustainability.

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