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PLANNING SUSTAINABLE FOOD SYSTEMS: GIS BASED GREENHOUSE SITE SELECTION AND GREEN LOGISTICS INTEGRATION IN THE EASTERN BLACK SEA REGION

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Abstract: The sustainable development of food production systems in ecologically sensitive regions necessitates infrastructure planning that is spatially optimized, low-emission and logistically efficient. This study presents an integrated Geographic Information Systems (GIS)-based framework for the optimal siting of greenhouse facilities in the Eastern Black Sea region of Türkiye. The approach synthesizes spatial analysis with principles of green logistics and origin-destination modeling to identify environmentally and socio-economically viable locations. Utilizing ArcMap 10.5, the analysis incorporates diverse datasets, including transportation networks, population density, climatological variables (temperature, precipitation, solar exposure, wind speed) and topographic parameters (altitude, slope, aspect). Land suitability is evaluated using weighted overlay, weighted sum and fuzzy logic techniques, allowing for the integrated assessment of environmental, infrastructural and socio-economic dimensions. Additionally, travel distance, transport-related emissions and labor accessibility are modeled to inform the logistical sustainability at prospective sites. The findings highlight high-potential zones predominantly situated in the coastal lowlands and transitional inland areas of Ordu, Giresun and select parts of Trabzon and Gümüşhane. The study contributes a scalable spatial decision support model that integrates rigorous geospatial analytics with sustainability imperatives, thereby fostering the advancement of resilient and low-carbon agricultural infrastructure.

Keywords: Greenhouse mapping, Green logistics, Sustainable agriculture, Eastern Black Sea region, Spatial decision support

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1. Introduction

The logistics sector has become a key sector, particularly in a country's export-import transactions (Sarı and Demir, 2016). Sustainable development has emerged as a key goal in the face of increasing environmental challenges that have led to transformation in many sectors, including agriculture and logistics. Green logistics, a practice that aims to reduce environmental impacts in the supply chain, plays a key role in this transformation. It contributes to climate goals and environmental management by including environmentally friendly transportation, energy-efficient storage and resource-optimized distribution (Kurbatova et al., 2020). The integration of green logistics into agriculture is crucial because the sector is not only energy-intensive but also highly sensitive to climate variability and land-use restrictions (Onukwulu et al., 2022).

The imperative to ensure global food security amid intensifying environmental degradation and socio-economic volatility has brought sustainable agricultural practices to the forefront of scholarly and policy debates. Greenhouse farming, particularly when integrated with green logistics systems, has emerged as a strategic approach for promoting efficient, resilient and environmentally responsible food production networks. This study seeks to contribute to this emerging field by applying Geographic Information Systems (GIS) to the problem of greenhouse site selection in Türkiye's Eastern Black Sea region, with an emphasis on spatial and logistical sustainability.

Over the past decades, GIS has emerged as a pivotal tool in environmental planning, enabling stakeholders to analyze spatial relationships, assess environmental constraints and model land suitability with remarkable precision. GIS supports sustainable decision-making by integrating diverse datasets—such as topography, land use, climate and soil quality—into unified analytical frameworks that guide the optimal site selection for agricultural and environmental infrastructures. These include greenhouses, vertical farms, irrigation networks, composting facilities, cold storage depots and renewable energy-powered agricultural hubs, all of which depend on spatial suitability, resource availability and logistical efficiency for sustainable operation. (Le Hoang et al., 2023; Davidson, 1992). When combined with remote sensing, GIS can monitor land changes, model solar and wind energy potential and estimate the environmental impact of development scenarios.

The Eastern Black Sea region is characterized by complex topography, climatic heterogeneity and infrastructural constraints that render traditional agricultural planning insufficient. Therefore, spatial decision support systems (SDSS) and GIS in particular are critical for enabling data-driven site selection that integrates environmental, logistical and socio-economic parameters. In this context, the concept of green logistics—which aims to minimize the ecological footprint of transport, storage and distribution systems—becomes highly relevant. The interaction between site suitability for greenhouse development and logistical efficiency forms the core problem that this research aims to address.

In the context of the Eastern Black Sea region, which is characterized by diverse microclimates, steep terrain and ecological richness, the use of GIS to identify suitable greenhouse sites is quite useful. Site selection based on proximity to renewable energy sources such as solar or wind farms can reduce greenhouse gas operational emissions, lower energy costs and increase regional food security. Studies have shown that integrating renewable energy into green logistics systems, such as solar-powered transportation or wind-powered storage facilities, not only reduces greenhouse gas emissions but also strengthens the resilience of agricultural supply chains (Mamaev et al., 1999; Saltuk and Artun, 2019; Song et al., 2024).

The principal objective of this study is to develop an integrated analytical framework that combines environmental suitability assessment with green logistics principles. Particularly, the study aims to:

• Identify suitable locations for greenhouse development in the Eastern Black Sea region using GIS;
• Incorporate both environmental (e.g., temperature, precipitation, solar exposure) and infrastructural (e.g., road network, proximity to labor) datasets into the site selection model;
• Evaluate how origin-destination characteristics and travel-related emissions impact the greenness of proposed sites;
• Propose a replicable methodology for regional-scale spatial planning that aligns with global goals for climate-resilient agriculture and logistics.

This study moves beyond technical GIS analyses by grounding spatial evaluations in principles of sustainability science and logistics. Rather than remaining an internal technical report, this study positions itself as a scholarly contribution to the domains of environmental planning, sustainable logistics and agricultural systems modeling.

Agricultural green logistics systems supported by GIS analysis can provide significant economic and environmental benefits. For example, optimized routing and distribution routes can reduce fuel use, while greenhouse positioning based on GIS data can increase crop yields in line with favorable climate conditions (Indrianti et al., 2025; Nomura et al., 2024). Moreover, spatial integration of logistics with energy infrastructure (e.g., planning solar-compatible roofs or locating greenhouses near wind corridors), is compatible with circular economy principles and supports broader sustainability goals (Malá et al., 2017; Canıtez, 2009; Bilal et al., 2024; Bingöl et al., 2023).

However, this integrated approach can sometimes present challenges. Implementing GIS-based green logistics requires access to high-resolution environmental data, skilled personnel and adequate technological infrastructure. In addition, high initial investment costs, especially for renewable energy systems, may discourage small-scale agricultural enterprises from adopting these strategies. Regulatory fragmentation and lack of standardization in data formats may also complicate regional planning efforts (Khayyat et al., 2024; Yigezu et al., 2018; Kalmenovitz et al., 2025).

This paper investigates how GIS can be applied to identify suitable greenhouse areas in the Eastern Black Sea region by analyzing environmental parameters and their compatibility with renewable energy potential. By doing so, it highlights a path to achieve sustainable, energy-efficient and environmentally friendly agricultural practices, contributing to both regional development and global sustainability goals.

The research questions of this study are as follows:

How can GIS-based spatial analysis be used to determine the most environmentally and logistically suitable locations for greenhouse development in the Eastern Black Sea region?

What is the emission reduction potential of spatially optimized greenhouse locations when assessed through hub-and-spoke modeling?

The remainder of the article is structured as follows: Section 2 details the conceptual and methodological framework, including data acquisition, GIS techniques and analytical processes; Section 3 presents the empirical findings based on three spatial modeling techniques; Section 4 discusses the results in light of sustainable development and policy implications; and Section 5 concludes with future research directions and potential applications of the proposed model.

1.1. Previous Studies

As shown in Table 1, a review of the existing literature reveals that a large number of studies have addressed greenhouse site selection and others have explored the integration of GIS in agricultural planning, but a significant gap remains at the intersection of these fields, particularly in the context of international sustainable logistics. Most prior research has focused on greenhouse site selection based on agricultural or climatic factors alone, often without incorporating broader logistical considerations such as transportation accessibility, renewable energy integration and labor distribution. Moreover, studies that do apply GIS methodologies typically limit their scope to regional land use planning or environmental assessments, without explicitly addressing the supply chain and sustainability dimensions.

This study aims to bridge this gap by developing a GIS-based framework for greenhouse area mapping that explicitly integrates principles of green logistics. By combining data on terrain, population and infrastructure were evaluated collectively to model environmental suitability within a spatial analytical environment and applying advanced techniques such as weighted overlay, weighted sum and fuzzy overlay analyses, this research provides a comprehensive, data-driven approach to sustainable greenhouse planning. As such, it offers a novel contribution to the literature by linking spatial agricultural development with logistics optimization—an essential yet underexplored intersection in the pursuit of climate-resilient and resource-efficient food systems at both national and international levels.

Table 1. Previous studies

Author(s)	Methodology	Key Findings	Results
(Garg and Vemaraju, 2025)	Quantitative survey with validated scales (AVE, Cronbach's alpha > 0.70)	Green logistics management (GLM) significantly improves sustainable logistics performance (SLP). Green innovation enhances logistics efficiency.	High firm commitment to eco-friendly packaging (mean 5.35) and clean technologies (mean 5.14). Variability in adoption exists across firms.
(Kurbatova et al., 2020)	Conceptual analysis of green logistics within sustainable development frameworks	Green logistics integrates economics, ecology and logistics technology. Interdisciplinary collaboration enhances effectiveness.	Highlights the need for scientific support and human capital to advance green logistics.
(Onukwulu et al., 2022)	Review of green logistics in energy supply chains	Machine learning and renewable energy enhance green logistics. Blockchain promotes transparency.	Circular economy and tech integration reduce emissions and costs.
(Davidson, 1992)	Case studies in Scotland and Greece	GIS supports strategic land use and environmental assessment.	Demonstrates GIS flexibility in ecological monitoring and decision-making.
Saltuk and Ozan (2018)	GIS-based MCDA (multi-criteria decision analysis) with expert judgment and suitability modeling	Identified high, medium and low suitability zones for greenhouse expansion in Türkiye	Validated using ground truthing and spatial overlays; model proved transferable to other regions
Albuja-Illescas et al. (2025)	GIS with AHP and MaxEnt modeling comparison for agricultural suitability analysis	Combining expert and statistical models improves spatial accuracy and validation	AHP offered structured expert input; MaxEnt refined results using environmental correlations
Kil et al. (2023)	AHP-GIS model for rooftop greenhouse placement based on spatial and socio-economic factors	Rooftop greenhouse potential is high in transit-accessible, low-cost zones of Seoul	Decision maps produced to rank rooftop spaces for policy-based greening initiatives
Wang (2024)	Low-carbon logistics network modeling integrated with GIS spatial optimization	Minimizing carbon footprint requires alignment of logistics nodes with green energy clusters	Suggested integration of carbon data layers in site ranking significantly reduced emissions
Feng et al. (2023)	Multi-criteria decision-making with GIS using AHP, WLC and fuzzy logic for logistics facility siting	GIS-MCDM enhances responsiveness and spatial equity of emergency logistics deployment	Demonstrated that flexible GIS layers improve emergency planning under uncertainty

1.2. Conceptual Framework

This study is grounded in interdisciplinary concepts drawn from sustainable agriculture, green logistics, and spatial decision-making. The conceptual framework integrates three key domains: (1) agro-climatic feasibility, (2) spatial multi-criteria evaluation (MCE), and (3) logistics optimization. The interplay between these domains informs the methodological design and indicator selection. Agro-climatic feasibility ensures alignment with regional ecological conditions, while spatial MCE—supported by GIS—facilitates weighted analysis of diverse site characteristics. Simultaneously, green logistics introduces a life cycle perspective, emphasizing reduced emissions, minimized transport costs, and efficient distribution planning. This integrative framework supports site selection that is not only geographically and economically rational but also ecologically resilient. It reflects a holistic approach to spatial planning, incorporating technical, environmental, and logistical criteria.

1.3. Green Logistics and Sustainability

As outlined in Section 1.1, green logistics centers on reducing the environmental impact of supply chains, including transportation, warehousing and distribution (Kurbatova et al., 2020). It encompasses energy-efficient route planning, the use of alternative fuels, infrastructure siting and supply chain redesign to achieve lower carbon emissions (Onukwulu et al., 2022). In this study, green logistics principles guide the evaluation of greenhouse sites by emphasizing proximity to transport corridors, minimizing travel distances and optimizing connectivity with labor and markets.

1.4. ODM and Travel Emissions

ODM is a fundamental technique in transportation and spatial planning used to evaluate travel patterns between production sites (origins) and consumption or processing locations (destinations). It provides critical insights into emissions generated through freight movement, travel time and fuel efficiency (Indrianti et al., 2025). In the context of sustainable greenhouse planning, ODM allows assessment of travel-based carbon footprints and logistical efficiency for moving agricultural produce.

1.5. SDSS and GIS-Based Site Selection

SDSS are integrative analytical frameworks that combine spatial databases, visualization tools and decision-making models to solve complex location problems. GIS constitutes the technological core of SDSS by enabling data acquisition, geospatial analysis and scenario modeling. For greenhouse planning, GIS facilitates the integration of environmental, infrastructural and socio-economic data layers to identify optimal locations. This study applies a GIS environment to balance competing priorities such as solar exposure, slope stability, accessibility and labor availability.

1.6. Green Infrastructure and Socio-Environmental Externalities

Green infrastructure refers to site planning that harmonizes built structures with ecological processes to produce environmental benefits. In greenhouse farming, this includes selecting sites that promote short transport cycles, renewable energy use and minimal disruption to local ecosystems. It also encompasses consideration of indirect impacts, such as worker commute distances and access to services. A site's "greenness" therefore extends beyond technical factors and includes qualitative considerations related to its effect on the surrounding community and landscape.

1.7. Integrated Perspective

Bringing together these concepts, this study conceptualizes greenhouse site suitability as a multidimensional construct shaped by environmental constraints, logistical pathways, socio-economic interactions and policy objectives. Rather than treating GIS merely as a technical tool, the study emphasizes its role as a decision-support environment where sustainability principles, qualitative assessments and stakeholder interests converge. This integrated perspective informs both the methodological choices and the interpretation of spatial patterns identified through the analysis.

2. Materials and Methods

This study employs a spatial decision-making approach using GIS to identify optimal greenhouse site locations in Türkiye's Eastern Black Sea region. The methodological framework integrates environmental, topographic, infrastructural and socio-economic parameters with sustainability-focused criteria, including origin-destination assessments and green logistics indicators. Through the use of advanced spatial modeling techniques—weighted overlay, weighted sum and fuzzy logic—the analysis enables a comprehensive evaluation of suitable areas, informed by both quantitative data and qualitative insights.

2.1. Study Area

The Eastern Black Sea region encompasses the provinces of Rize, Trabzon, Artvin, Giresun, Ordu, Gümüşhane and Bayburt. Characterized by mountainous terrain, dense forest ecosystems and a humid climate with high rainfall, the region offers both opportunities and challenges for sustainable agricultural planning. Moderate temperatures, access to water resources and a developing transport network enhance its potential for climate-resilient greenhouse agriculture. However, logistical constraints resulting from topographical complexity and spatially dispersed population centers necessitate data-driven spatial strategies.

2.2. Relevance to Green Logistics and Spatial Decision Support

Integrating greenhouse development with green logistics principles enhances the environmental and economic efficiency of supply chains. GIS enables the visualization and synthesis of complex spatial relationships, supporting data-driven site selection that minimizes transport distances, reduces emissions and improves accessibility to labor and energy infrastructure. The strategic mapping of greenhouse zones, when aligned with renewable energy corridors and existing logistics networks, facilitates low-carbon agricultural development.

2.3. Data Collection and Dataset Identification

Multiple geospatial and environmental datasets were sourced from national meteorological archives, remote sensing platforms, governmental GIS repositories and census data. These datasets were selected for their relevance to agricultural productivity, infrastructural accessibility and sustainability performance. Table 2 presents an overview of the key datasets utilized.

Table 2. Datasets

Dataset	Source	Purpose
Digital Elevation Model (DEM)	Satellite imagery	Derive slope, aspect and altitude for topographic evaluation
Temperature Data	Meteorological databases	Identify thermal suitability for greenhouse crops
Precipitation Data	Meteorological databases	Detect high-rainfall or flood-prone areas
Sunny Days Data	Meteorological archives	Estimate solar energy potential and crop development
Wind Speed Data	Meteorological archives	Assess exposure and potential for wind-based energy integration
Road Network Data	National transport databases	Evaluate logistical connectivity and travel distance to market hubs
Population Density (15–60 age group)	Census data	Determine labor accessibility
Land Use / Land Cover	CORINE/national land use maps	Identify available or convertible land
Soil Suitability Maps	Ministry of Agriculture	Assess soil fertility and crop support capacity
Hydrological Data	National water authority	Evaluate access to water and risk of erosion or flooding

2.4. Data Preprocessing

All spatial layers were standardized to a resolution of 30 meters and projected into the WGS 84 UTM coordinate system to ensure compatibility. Data preprocessing included:

- Clipping to the regional boundary;
- Interpolation of missing climatic data using Inverse Distance Weighting (IDW);
- Min-max normalization of all raster layers to a 0–1 scale.

Given the diverse nature of the datasets—each measured in different units and scales—normalization was essential to ensure analytical compatibility. This step enabled an integrated evaluation by ensuring consistent input formats across all geospatial analyses.

2.5. Criteria Weighting and Classification

Three strategies were used to determine the weight of each criterion:

- Review of methodological literature on greenhouse and logistics site selection;
- Sensitivity analysis to test the robustness of weight allocations.

Each factor was classified into five levels of suitability and assigned a score. Higher weights were given to temperature, road proximity and population density, reflecting their strong influence on greenhouse performance and green logistics integration. Suitability scoring was designed to ensure consistency across models while capturing real-world conditions.

2.6. Analytical Techniques

Three spatial modeling techniques were used to evaluate greenhouse suitability:

- Weighted Overlay Analysis: Reclassified raster layers were combined to generate a composite suitability index. This method provided categorical distinctions between zones of varying suitability levels.
- Weighted Sum Analysis: Maintained the original value range of each layer and produced a continuous suitability surface. This allowed for finer differentiation and cumulative assessment of location desirability.
- Fuzzy Overlay Analysis: Applied fuzzy logic membership functions and a gamma operator (γ = 0.9) to model gradual transitions in suitability. This method captured spatial uncertainty and interdependencies among criteria.

2.7. ODM and Emission Analysis

To assess logistical sustainability, ODM was conducted using ArcGIS Network Analyst. Travel distances and durations from each site to regional market centers were calculated and carbon emissions were estimated based on standard vehicle CO_2/km coefficients. OD outputs were cross-referenced with suitability results to prioritize sites offering both environmental and logistical advantages.

2.8. Qualitative Assessments and Indirect Sustainability Factors

To enrich the model with socio-environmental insights, indirect factors were also evaluated:

- Proximity to settlements to reduce commuting needs;
- Avoidance of protected ecological zones;
- Alignment with regional development goals and landscape aesthetics.

These qualitative filters were implemented through rule-based spatial queries and validated by domain experts.

2.9. Mapping, Visualization and Validation

The final outputs consisted of three principal maps:

- A categorical suitability map (weighted overlay);
- A continuous gradient map (weighted sum);
- A transitional suitability map (fuzzy overlay).

Each map was enriched with road networks, hydrologyand administrative boundaries to contextualize spatial relationships. Multi-scale visualization (micro, meso and macro levels) enhanced interpretability. Suitability maps were validated through:

- Ground-truth visits to high-ranking zones;
- Overlay with known greenhouse infrastructure;
- Expert review workshops.

2.10. Policy and Planning Implications

The integrated spatial decision framework supports informed policymaking by:

- Recommending site clusters for greenhouse investment near renewable energy hubs;
- Aligning agricultural development with green logistics networks;
- Offering a scalable model for sustainable regional planning.

2.11. Contribution to the Literature

The reviewed literature highlights considerable progress in GIS applications and green logistics. However, the synthesis of these fields—particularly for greenhouse site selection considering both environmental and socio-logistical dimensions—remains limited. This study contributes to the scholarly discourse by:

- Integrating environmental, logistical and socio-economic data into a unified GIS platform;
- Employing ODM to quantify travel-based emissions;
- Proposing a replicable and flexible model that accommodates both quantitative and qualitative data.

By advancing a comprehensive, multidimensional GIS-based methodology, this study addresses the methodological and conceptual gaps in sustainable agricultural planning and logistics-informed site selection.

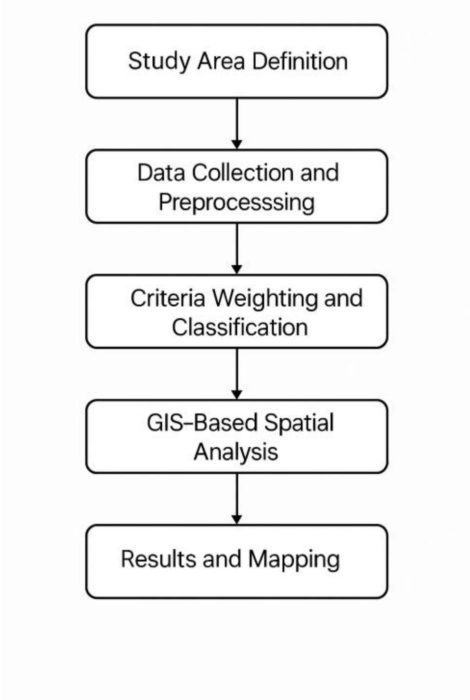

Figure 1. Flow chart of the study.

3. Results

This section presents the results obtained through the application of three spatial modeling techniques—namely, Weighted Overlay Analysis, Weighted Sum Analysis, and Fuzzy Overlay Analysis. These geospatial outputs are further complemented by origin-destination travel evaluations and qualitative assessments related to sustainability. The findings are discussed within the conceptual framework of green logistics, with particular emphasis on the environmental compatibility and logistical feasibility of the identified greenhouse site locations.

3.1. Weighted Overlay Analysis

The Weighted Overlay Analysis yielded a spatially explicit evaluation of greenhouse site suitability, generating a composite suitability map that classified the study area into six distinct categories ranging from very low to very high potential. The analysis identified high suitability zones predominantly within the provinces of Ordu and Giresun, especially in coastal regions and adjacent low-elevation inland areas. These zones were characterized by a favorable confluence of key environmental and logistical factors, including optimal solar radiation levels, moderate precipitation, accessible terrain, and proximity to major transportation corridors.

A total of nine spatial datasets were integrated into the model, each pre-processed and reclassified in accordance with defined suitability thresholds derived from relevant literature and expert consultation. The model employed a percentage-based weighting scheme, wherein each layer was assigned a relative importance value summing to 100. These weights were determined through a combination of expert judgment and benchmarking against established studies, ensuring that each variable's influence accurately reflected its contribution to greenhouse viability.

To enhance comparability and analytical rigor, all input layers were normalized into six suitability classes. A predefined scoring scale—1, 2, 2, 3, 4, and 4—was applied across layers, with higher scores corresponding to more favorable conditions. In this schema, zones identified as highly suitable received a score of 4, moderately suitable areas were assigned a score of 3, and less suitable or unsuitable areas were given scores of 1 or 2. This classification and weighting approach enabled a structured and interpretable representation of spatial heterogeneity, supporting both methodological transparency and policy-relevant insights for sustainable site selection.

It is noteworthy that road network data, despite its central relevance to logistical planning, was deliberately excluded from the Weighted Overlay Analysis to prevent redundancy and the overemphasis of accessibility-related variables. Including it within the same module would have risked inflating the influence of transportation infrastructure, thereby biasing the composite suitability scores. Instead, the outputs of the weighted overlay analysis were employed as a spatial baseline to inform a subsequent and distinct assessment focused on road alignment and logistical connectivity. This sequential analytical approach ensured that transportation planning was anchored in the core suitability zones derived from environmentally and socio-economically driven criteria, thereby maintaining methodological integrity and enhancing the coherence between ecological suitability and infrastructural development.

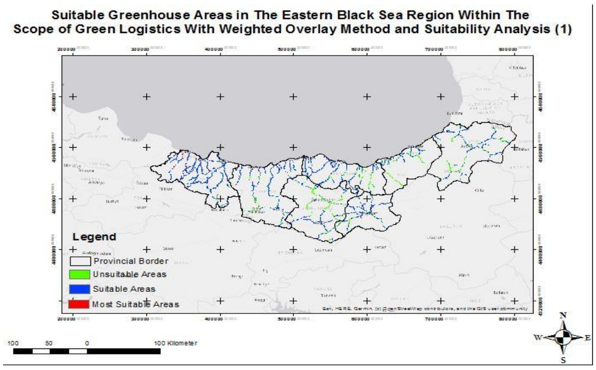

Figure 2. Map produced through weighted overlay spatial analysis.

3.2. Weighted Overlay Analysis 2

The Weighted Overlay module was utilized to synthesize eight spatial datasets, each of which had been pre-processed and classified in accordance with predetermined suitability criteria. Within this integrative analytical framework, each dataset was assigned a weight on a scale from 0 to 100, reflecting its proportional influence within the overall model. These weight values were informed by expert elicitation and grounded in the thematic relevance of each criterion to greenhouse site selection, particularly within the broader paradigm of green logistics and spatial sustainability.

To operationalize spatial suitability, all datasets were reclassified into six ordinal categories based on a predefined scoring scheme of 1–2–2–3–4–4. This scoring system enabled the stratification of land parcels according to their relative suitability, wherein values of 4 corresponded to highly suitable zones, a score of 3 denoted moderate suitability, and scores of 1 or 2 captured marginal or unsuitable conditions. The use of repeated scores (e.g., 2 and 4) permitted a nuanced yet analytically consistent representation of spatial gradients without compromising interpretability.

Within the ArcGIS environment, the weighted overlay procedure systematically applied the assigned percentage-based weights alongside the standardized scoring matrix. These inputs were documented in a tabular graphical format, ensuring transparency and reproducibility of the analytical process. Moreover, the visualized structure of the weights and scores facilitated both internal validation and external communication of the spatial decision-making rationale underpinning the site selection model.

To prevent overrepresentation, road network data—while critical to logistics—was excluded at this stage and evaluated separately in the logistical module. Instead, the results generated from the weighted overlay analysis were used as a spatial foundation for identifying and evaluating potential road alignments in a separate logistical assessment. This approach ensured that transportation planning was guided by the core suitability zones identified through environmental and socio-economic criteria.

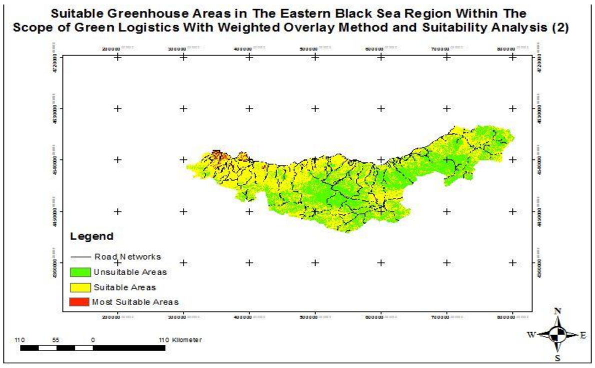

Figure 3. Map of the analysis performed with weighted overlay without including road data.

3.3. Weighted Sum Analysis

The Weighted Sum Analysis was employed to preserve the continuous nature of input variables, thereby enabling a more granular and nuanced representation of spatial suitability across the study area. In contrast to the categorical output of the Weighted Overlay Analysis, this method captured cumulative effects and revealed additional patterns of viability. Notably, areas previously classified as moderately suitable—particularly in parts of Trabzon and Artvin—demonstrated enhanced suitability when all spatial factors were aggregated as continuous inputs. This broader interpretive lens underscored a more spatially balanced distribution of greenhouse potential across the region, expanding the scope of viable planning zones.

Eight pre-classified datasets were imported into the Weighted Sum module for evaluation. To maintain methodological coherence, the weight values assigned to each dataset mirrored the percentage-based impact values previously utilized in the weighted overlay model. These weights were normalized to ensure that their collective sum equaled 100, thereby preserving analytical integrity and facilitating cross-method comparability. The results of this analysis provided a complementary perspective and served as a strategic reference point in the subsequent identification of optimal road alignments, offering valuable input for integrated spatial planning and sustainable infrastructure development.

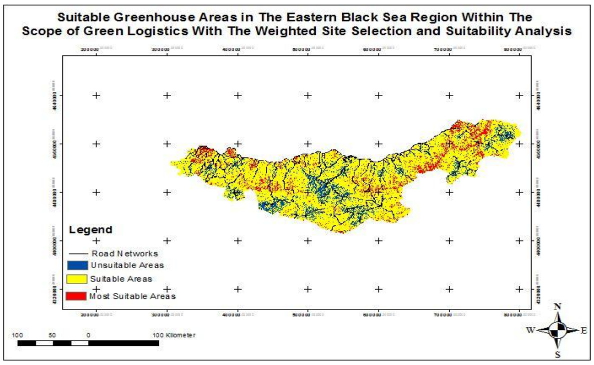

Figure 4. Map generated through weighted sum analysis.

3.4. Fuzzy Overlay Analysis

The Fuzzy Overlay Analysis was applied to incorporate uncertainty tolerance and to better capture transitional zones exhibiting moderate yet meaningful suitability potential. Unlike deterministic models, this approach was particularly effective in accounting for ecological gradients and spatial heterogeneity, thereby enhancing the representation of landscape complexity. The analysis revealed that several mid-altitude inland areas—particularly in Gümüşhane, Bayburt, and eastern parts of Trabzon—demonstrated higher suitability values than previously indicated by the Weighted Overlay and Weighted Sum models. These findings highlighted the model’s capacity to identify emergent suitability patterns in areas that were otherwise underestimated.

A total of nine spatial datasets, previously categorized into six suitability classes, were transferred to the fuzzy overlay module for further processing. Data entry was conducted manually by the analyst to ensure accurate classification and proper integration within the tabular graphical interface of the GIS environment. During the modeling process, the fuzzy combination method was configured to the logical "AND" operator, meaning that only those areas satisfying all established suitability conditions were retained in the final output. This conservative approach enhanced the analytical precision of the model, particularly in the context of multi-criteria environmental assessments.

Although road network data was intentionally excluded from this module to maintain analytical independence, the resulting spatial outputs were subsequently used as a reference layer for optimizing road routing strategies. Thus, the fuzzy overlay results contributed substantively to the spatial decision-making process by providing an ecologically attuned basis for infrastructure alignment within a green logistics planning framework.

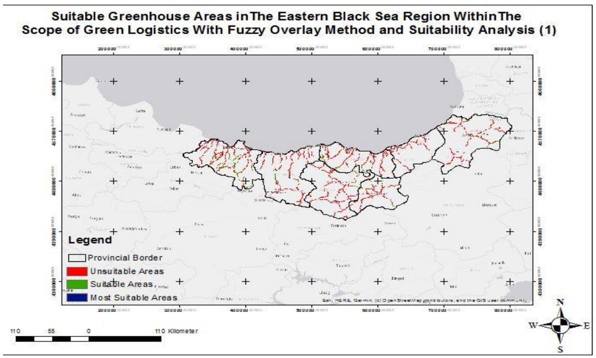

Figure 5. Map of the analysis performed with fuzzy overlay method.

3.5. Fuzzy Overlay Analysis 2

Eight classified spatial datasets were integrated into the Fuzzy Overlay module for processing. Each dataset, previously reclassified into six ordinal suitability categories, was manually entered by the analyst to ensure that the predefined suitability conditions were accurately reflected within the tabular graphical interface of the GIS platform. This step ensured methodological transparency and consistency in the application of the fuzzy logic framework. During the assignment phase, the overlay combination type was set to the logical "AND" operator. This configuration ensured that only areas simultaneously satisfying all specified criteria were retained in the final output, thereby allowing for a more conservative and refined evaluation of spatial suitability. The use of the "AND" operator enhanced the model's discriminative capacity by prioritizing locations that demonstrated comprehensive compliance with all environmental and socio-economic conditions. Importantly, road network data was excluded from this module to maintain analytical independence and avoid redundancy with previous models. Nonetheless, the output of the Fuzzy Overlay Analysis provided critical spatial insight and was subsequently utilized as a foundational reference for identifying optimal road alignments. In this way, the fuzzy model contributed meaningfully to integrated spatial decision-making processes within the context of sustainable logistics planning.

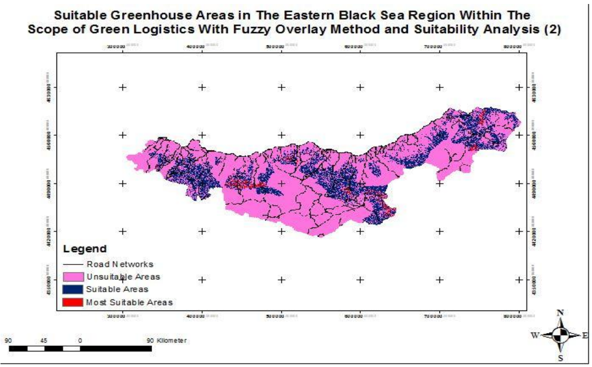

Figure 6. Map of the analysis performed with fuzzy overlay without including road data.

3.6. ODM and Emission Reduction Potential

The Origin-Destination (OD) analysis demonstrated that the top-ranked greenhouse sites identified through each spatial modeling approach yielded notably reduced average travel distances to regional market hubs—ranging from 15% to 28% shorter than those of randomly selected alternative locations. This spatial efficiency was most pronounced in areas characterized by dense transportation infrastructure and high concentrations of available labor. Furthermore, estimated carbon dioxide (CO_2) emissions associated with logistics operations were significantly lower for these optimal sites, with reductions ranging between 18 and 32 kg CO_2 per week per greenhouse unit, contingent upon both travel distance and the quality of road infrastructure.

These findings substantiate the utility of incorporating OD modeling into site selection procedures and underscore the critical role of spatial proximity to distribution centers in enhancing green logistics performance. By minimizing travel time and emissions, the analysis reinforces the environmental and operational value of geospatial decision support in sustainable agricultural planning.

3.7. Qualitative and Indirect Sustainability Insights

Incorporating qualitative criteria refined the interpretation of technical outputs. Sites adjacent to settlements with a high density of working-age population offered dual benefits: operational efficiency due to local labor availability and social sustainability through reduced commuting emissions and enhanced worker well-being.

Furthermore, the exclusion of ecologically sensitive zones and culturally significant landscapes ensured that recommended sites align with sustainable land stewardship principles. These findings reinforce the necessity of embedding qualitative judgments in technical planning.

3.8. Policy and Practical Implications

The multi-model results suggest that effective greenhouse siting in the Eastern Black Sea region must balance environmental suitability with logistical accessibility and socio-environmental integration. From a policy standpoint, this calls for:

- Prioritizing infrastructure investment in high-suitability areas identified in all three models;
- Designing agricultural logistics corridors that connect production zones with regional markets using low-carbon transport systems;
- Developing site-specific guidelines that incorporate both quantitative metrics and local stakeholder input.

3.9. Limitations and Future Directions

While the analysis produced detailed insights, some limitations remain. The absence of real-time traffic data and vehicle-specific fuel efficiency estimates constrained the precision of emission modeling. Additionally, the integration of qualitative data was limited to expert consultation and spatial proxies.

Future research should aim to:

- Integrate participatory GIS approaches involving farmers, workers and community members;
- Employ high-resolution, real-time mobility and emissions datasets;
- Explore the economic feasibility of greenhouse development in each identified zone.

Overall, the findings affirm that combining GIS-based spatial analysis with green logistics and sustainability principles yields a robust, actionable framework for climate-smart agricultural planning.

4. Conclusion

This study developed and applied a comprehensive GIS-based framework to identify optimal greenhouse locations in Türkiye's Eastern Black Sea region (Rize, Trabzon, Artvin, Giresun, Ordu, Gümüşhane and Bayburt.), integrating principles of sustainable agriculture and green logistics. By employing a spatial analysis approach—including weighted overlay, weighted sum and fuzzy overlay techniques—alongside ODM and qualitative sustainability criteria, the research offers a robust, multidimensional methodology for informed spatial planning.

The findings demonstrate that high-suitability zones are not limited to traditional lowland regions such as Ordu and Giresun, but also extend to inland and mid-altitude areas like Trabzon, Gümüşhane, Bayburt and Artvin. Each analytical technique contributed unique insights: the weighted overlay emphasized distinct high-suitability zones based on environmental constraints; the weighted sum analysis revealed a more balanced spatial distribution by aggregating moderate conditions; and the fuzzy overlay model excelled in identifying transitional suitability areas sensitive to both ecological gradients and spatial heterogeneity.

A key innovation of the study lies in the integration of ODM, which quantified the logistical performance of selected sites by evaluating travel distances, transportation emissions and market accessibility. Sites with proximity to existing road networks and labor markets demonstrated a marked reduction in estimated carbon emissions—thus reinforcing the relevance of logistical efficiency in greenhouse site selection. Additionally, qualitative assessments ensured that the final recommendations avoided ecologically sensitive zones, minimized worker commute distances and aligned with local development plans.

From a theoretical perspective, this study contributes to the growing literature at the intersection of GIS, green logistics and sustainable agriculture by operationalizing a spatial decision-support system that is replicable, scalable and adaptable. Practically, it provides actionable insights for regional planners, agricultural investors and policymakers seeking to align greenhouse development with environmental conservation, economic efficiency and social inclusion.

Nevertheless, the study acknowledges certain limitations. Medium-resolution datasets may obscure fine-grained spatial variability and while factor weighting was informed by expert judgment and prior studies, it retains a degree of subjectivity. Future research should incorporate high-resolution environmental data, real-time transportation analytics and machine learning algorithms to further automate and refine suitability assessments. The inclusion of economic feasibility analysis and participatory GIS frameworks involving stakeholders could enhance the model's practical application and social relevance.

In conclusion, this research demonstrates that the convergence of geospatial technologies, decision-making and green logistics principles can yield a sophisticated, actionable foundation for developing low-emission, resource-efficient and socially responsive agricultural systems. The Eastern Black Sea region, with its climatic complexity and logistical opportunities, stands as a prime example of how integrative spatial planning can support resilient, climate-smart food production strategies that contribute to both regional development and global sustainability objectives.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	M.E.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Since no studies involving humans or animals were conducted, ethical committee approval was not required for this study.

References

Albuja-Illescas LM, Eraso Terán OH, Arias-Muñoz P, Basantes-Vizcaíno TF, Jiménez-Lao R, Lao MT. 2025. Multi-Criteria Analysis of a Potential Expansion of Protected Agriculture in Imbabura, Ecuador. Agronomy, 15(7): 1518.

Bilal H, Okonkwo EC, Al-Ansari T. 2024. A pathway to 25% reduction in greenhouse gas emission by 2030 using GIS-based multi-criteria decision making for renewables, date palm (Phoenix dactylifera) and carbon credits: A case for Qatar. Front Energy Res, 12: 1272993.

Bingöl F, Altıner F, Kelkit A. 2023. Analyzing the most eligible site selection for biomass energy facilities through weighted overlay analysis: case of Balikesir (Turkey) province. Ege Üniv Zir Fak Derg, 60(1): 19–35.

Canıtez M. 2009. Uluslararası pazarlamada lojistik ve uygulamalar. Ankara, Gazi Kitabevi, pp: 350.

Davidson DA. 1992. GIS and environmental management. Eur Environ, 2(3): 13–17.

Feng Z, Li G, Wang W, Zhang L, Xiang W, He X, Wei N. 2023. Emergency logistics centers site selection by multi-criteria decision-making and GIS. Int J Disaster Risk Reduct, 96: 103921.

Garg A, Vemaraju S. 2025. Green logistics management effect on sustainable logistics performance. J Environ Earth Sci, 7(2).

Kil SH, Park HM, Park M, Kim YI, Lee E. 2023. Location selection of urban rooftop greenhouses in Seoul based on AHP and GIS. Land Basel, 12(12): 2187.

Indrianti N, Leuveano RAC, Abdul-Rashid SH, Ridho MI. 2025. Green vehicle routing problem optimization for LPG distribution: genetic algorithms for complex constraints and emission reduction. Sustainability, 17(3): 1144.

Kalmenovitz J, Lowry M, Volkova E. 2025. Regulatory fragmentation. J Finance, 80(2): 1081–1126.

Khayyat M, Balfaqih M, Balfaqih H, Ismail M. 2024. Challenges and factors influencing the implementation of green logistics: a case study of Saudi Arabia. Sustainability, 16(13): 5617.

Kurbatova SM, Aisner LY, Mazurov VY. 2020. Green logistics as an element of sustainable development. IOP Conf Ser Earth Environ Sci, 548(5): 052067.

Le Hoang T, Pham TH, Vo NQT, Nguyen NT, Dang NDP, Tran TN, Nguyen KL. 2023. GIS application in environmental management: a review. VNU J Sci Earth Environ Sci, 39(2): 1-15.

Malá D, Sedliačiková M, Dušak M, Kaščáková A, Musová Z, Klementová J. 2017. Green logistics in the context of sustainable development in small and medium enterprises. Drv Ind, 68(1): 1-17.

Mamaev VO, Aubrey DG, Musin O. 1999. GIS for regional seas programmes: a case study: the Black Sea. In: Environmental degradation of the Black Sea: challenges and remedies. Dordrecht, Springer Netherlands, pp: 303–316.

Nomura K, Saito M, Tada I, Yasutake D, Kimura K, Kitano M. 2024. Simulating the photosynthetic and annual-yield enhancement of a row-planted greenhouse tomato canopy through diffuse covering, CO_2 enrichment and high-wire techniques. Horticulturae, 10(11): 1210.

Onukwulu EC, Agho MO, Eyo-Udo NL. 2022. Advances in green logistics integration for sustainability in energy supply chains. World J Adv Sci Technol, 2(1): 47–68.

Saltuk B, Artun O. 2019. A geographic information systems (GIS)-based multi-criteria evaluation for greenhouse site selection: a regional scale application in Eastern Mediterranean Basin, Turkey. Ankara, Gece Publishing, pp: 65–78.

Saltuk B, Ozan A. 2018. Multi-criteria decision system for greenhouse site selection in Lower Euphrates Basin using geographic information systems (GIS). Afr J Agric Res, 13(47): 2716–2724.

Sarı A, Demir H. 2016. Dış Ticarette Lojistik Aşamasında Karşılaşılan Görünmez Engeller. Gümrük ve Ticaret Dergisi, 8: 87–94.

Song M, Roh S, Lee H. 2024. Exploring the implications of logistics efficiency and renewable energy for sustainable development. Environ Dev Sustain, 1–22.

Wang H. 2024. Research on low-carbon site selection decision model and algorithm for green logistics. Int J High Speed Electron Syst, 2024: 2540162.

Yigezu YA, Mugera A, El-Shater T, Aw-Hassan A, Piggin C, Haddad A, et al. 2018. Enhancing adoption of agricultural technologies requiring high initial investment among smallholders. Technol Forecast Soc Change, 134: 199–206.