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Land Suitability for Seasonal Crops: Limiting Factors and SDG-Aligned Management Strategies

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SPECIAL ISSUE ARTICLE

Land Suitability for Seasonal Crops: Limiting Factors and SDG-Aligned Management Strategies

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ABSTRACT

A land evaluation study of Muara Batang Toru Sub-district is essential to determine its development prospects for seasonal crops. This study evaluates land suitability for six seasonal plants, including red chili, cucumber, shallot, tomato, eggplant, and bitter melon, in Muara Batang Toru Sub-district, South Tapanuli Regency. This study employs a survey method, integrating field observations and laboratory analysis with predetermined criteria based on a combination of internationally recognized standards and local conditions. Geographic information systems are used to map the actual and potential land suitability classes for vegetable crops. The findings indicate that most of the actual land suitability classes fall under marginally suitable (S3) and currently not suitable (N1) categories, primarily due to limiting factors such as water availability (wa), low nutrient retention (nr), suboptimal rooting media (rc), and high rainfall (tc). Proper management practices, such as making drainage systems and raised beds, applying 15-25 kg of organic fertilizer per hectare annually, and applying lime or dolomite, can improve the land suitability class to moderately suitable (S2) or highly suitable (S1). Effective management practices, including establishing drainage systems and planting beds, applying 15–25 tons/ha of organic fertilizer annually, can improve the land suitability classification to moderately suitable (S2) or even highly suitable (S1). Commodities such as red chili, tomato, and bitter melon have the potential for significant productivity gains with these interventions. Implementing intercropping and crop rotation systems is recommended to optimize yields, maintain environmental sustainability, enhance agricultural output, and promote the socio-economic stability in Muara Batang Toru Sub-district. This research also contributes to achieving the Sustainable Development Goals (SDGs).

Keywords: Highly suitable, Land management, Limiting factors, Nutrient retention, SDGs

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Introduction

Agriculture plays an essential role in achieving the Sustainable Development Goals (SDGs), especially Goals 2 (ending hunger), Goal 12 (sustainable consumption and production), Goal 13 (Mitigating Climate Change): Increasing agricultural resilience to climate change by selecting crops that are appropriate to local conditions, and Goal 15 (conserving terrestrial ecosystems) from the 17 SDGs. Agriculture in Muara Batang Toru Sub-district, South Tapanuli Regency, has significant potential to contribute to these goals. Red chili, cucumber, shallot, tomato, eggplant, and bitter melon are strategic commodities that support food security, sustainable consumption, climate change mitigation and adaptation, and ecosystem preservation.

Vegetable farming in Muara Batang Toru Sub-district, South Tapanuli Regency, particularly red chili, cucumber, shallot, tomato, eggplant, and bitter melon, has great potential to support the achievement of SDGs targets. However, this potential is challenged by land conditions and other limiting factors that hinder agricultural productivity. Key obstacles include high rainfall, low nutrient retention, suboptimal rooting media, and limited water availability. Therefore, a land evaluation study is needed to assess development prospects and appropriate management strategies. Vegetable crops such as red chili, cucumber, shallot, tomato, eggplant, and bitter melon are high-value commodities that meet local market demand and contribute to food price stabilization. Evaluating land suitability is essential for assessing an area's capacity to support sustainable crop growth. This process involves analyzing and matching biophysical land factors to specific crop requirements. This method allows for the identification of actual land potential and the development of technical recommendations to address limiting factors. By employing this approach, it is possible to identify the land's actual potential and develop technical recommendations to address the limiting factors.[1–4] We employed survey methods, laboratory analyses, and geographic information systems (GIS) to map actual and potential land-suitability classes for vegetable crops. GIS facilitates the integration of various biophysical variables, enabling the creation of a comprehensive land suitability map.

To optimize agricultural potential and support the achievement of the SDGs, a comprehensive evaluation of land suitability for cultivating red chili, cucumber, shallot, tomato, eggplant, and bitter melon is necessary. This evaluation will consider the land's biophysical factors alongside each crop's specific requirements to develop appropriate land management recommendations that address existing obstacles. While previous studies have examined land suitability for various crops,[4–7] research on annual crops in this region regarding the SDGs remains limited. Therefore, this study is essential.

Research on the suitability of vegetable cropland in Muara Batang Toru Sub-district, South Tapanuli Regency, is essential, particularly for its role in supporting several Sustainable Development Goals (SDGs), including SDGs 1,2,8, 11,12,13, and 15. Improving the quality and quantity of seasonal plant commodities can be achieved through land evaluation, which compares land-use requirements with land characteristics.[1,4–6] Improper land management that does not align with the land's characteristics can hinder agricultural productivity and ultimately lead to crop failure.[8–11] A comprehensive planning approach relies on physical environmental information obtained through soil surveys and subsequent land evaluation.[12–15] The results of land evaluation provide information on appropriate land use, including suitability for seasonal crops. However, limited knowledge and understanding among farmers regarding land characteristics and crop selection, along with challenges in obtaining accurate land data, can hinder their ability to determine land suitability.

To achieve self-sufficiency in Muara Batang Toru Sub-district, South Tapanuli Regency, the development of seasonal crops has been prioritized as a key sector of the agricultural sector to support the local economy. The government also aims to establish the sub-district as a center for seasonal crop production in North Sumatra. Although the region has vast agricultural potential, development efforts have not yet been based on land suitability assessments. This study aims to evaluate the actual and potential land suitability in the area to support the achievement of the SDGs goals. This research is expected to contribute significantly to sustainable agricultural development and the broader goals of sustainable development. In addition, by identifying key limiting factors such as high rainfall, low soil nutrient retention, and limited water availability, this study provides valuable insight into overcoming environmental challenges that affect agricultural productivity.

Materials and methods

The study area

This research was conducted in Muara Huta Raja Village, Huta Raja Village, and Bandar Hapinis Village, Muara Batang Toru Sub-district, South Tapanuli Regency, North Sumatra Province, Indonesia Fig. 1. This study focused on the Muara Batang Toru

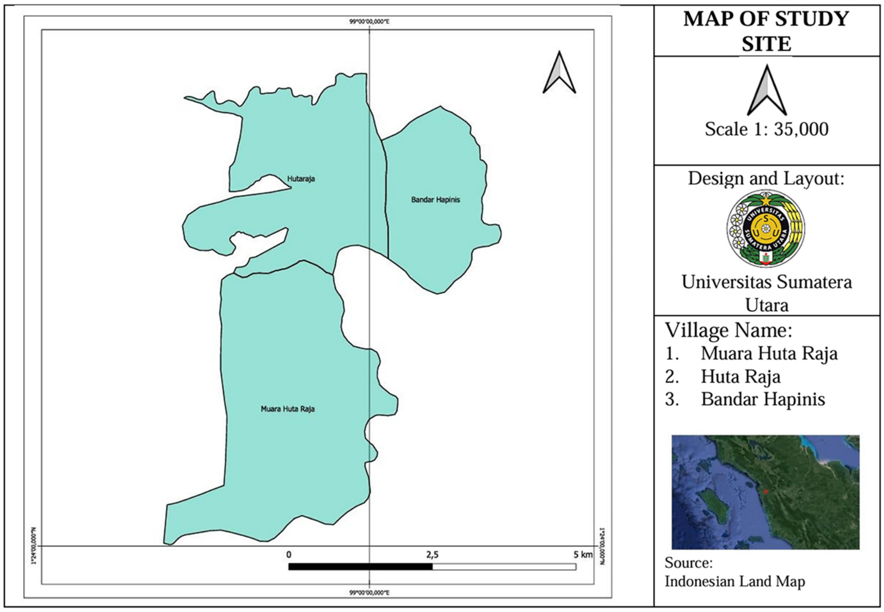

Fig. 1. Map of study site.

Sub-district due to its significant geographical and environmental potential for agricultural development, particularly vegetable cultivation. The area's diverse landforms, soil types, and climatic conditions provide a suitable foundation for analyzing land suitability across various crops. Its unique agroecological characteristics, including a tropical climate with abundant annual rainfall, diverse soils, and varied topography, present opportunities and challenges for agricultural growth. These unique characteristics, combined with the region's significance in seasonal crop production and its capacity to support the achievement of the SDGs, establish Muara Batang Toru as a highly suitable site for this study.

Methods

We employed a survey method at the research location, beginning with the selection of soil sampling locations based on land units. The criteria for selecting soil sampling locations using purposive sampling are based on land units. Land units are used as a criterion to ensure that soil sampling captures the full variability of biophysical factors across the study area. This systematic approach minimizes bias and ensures comprehensive data collection. A land unit has uniform characteristics. Since the land unit is considered homogeneous, sampling is carried out at only one or a few locations that represent the overall characteristics of the land unit. A land unit map was created using the overlay technique in a GIS application,[16–19] integrating altitude, soil, slope, and the administrative map of Muara Batang Toru Sub-district. We use ArcGIS software because it can help with overlay analysis to integrate and process multiple spatial datasets. This allowed for accurate delineation of land units and precise mapping of land suitability classes, facilitating clear visualization of results. Field surveys were conducted to collect data on land condition and other relevant information. Soil samples were then analyzed in the laboratory, and the results were used to determine the actual land suitability class for six vegetable commodities by comparing them with the area's land characteristics. The matched survey data were presented in a land suitability table for each crop based on its limiting factors. These limiting factors are land characteristics that restrict agricultural productivity, including soil pH, texture, rainfall, and humidity. Soil pH influences nutrient availability, while soil texture determines the drainage capacity and aeration.

Next, actual and potential land suitability classes were mapped using GIS.[20–23] Geographic Information Systems was employed to create detailed land suitability maps, enabling clear visualization of suitability classes.[23,24] This approach provides location-specific recommendations for vegetable crop management, enhancing decision-making for agricultural development.

Data analysis

The predetermined criteria used in this study for land suitability evaluation were established based on a combination of internationally recognized standards and local conditions. Specifically, the criteria were primarily adapted from the FAO Land Evaluation Framework, which provides standardized guidelines for assessing land suitability according to crop requirements and land characteristics. In addition, these criteria were matched using findings from local studies and field data specific to Muara Batang Toru Sub-district, ensuring that the evaluation reflects both global best practices and the unique biophysical conditions of the study area. The analysis of actual and potential land suitability classes was conducted using the matching method.[1,4,6,19] Field observations and laboratory analysis were compared with land characteristics for six vegetable crops: red chili, cucumber, red onion, tomato, eggplant, and bitter melon. Suitability class criteria followed FAO (1976),[25] categorized as follows:

1. Highly suitable (S1), meaning it meets all requirements without constraints.
2. Moderately suitable (S2), meaning it meets most requirements with minor constraints.
3. Marginally suitable (S3) meets the requirements but with significant constraints.
4. Not suitable (N), meaning it does not meet the requirements for cultivation.

This method compares laboratory and survey results with plant characteristic data from the literature.[1,4,17] The distribution of actual and potential land suitability classes for red chili, cucumber, shallot, tomato, eggplant, and bitter melon was analyzed using GIS.

Results and discussion

Actual and potential land suitability for red chilies, cucumbers, shallots, tomatoes, eggplants, and bitter melon

The analysis results of actual and potential land suitability for red chilies, cucumbers, shallots, tomatoes, eggplants, and bitter melon are presented in Tables 1 to 6.

Based on Table 1, the actual land suitability for chili in the three villages in the Muara Batang Toru Sub-district, South Tapanuli Regency, is classified as marginally suitable (S3), with the primary limiting factors being water availability (wa), rooting media (rc), and nutrient retention (nr).[4,8,15,17] Water availability (wa) refers to the sufficiency of water throughout the chili plants' growth cycle. Water stress or inadequate irrigation can hinder plant growth and reduce yields. To address this issue, implementing drainage ditches and raised beds can help manage excess water and improve water distribution. Rooting media (rc) refers to the soil's ability to provide an adequate environment for plant roots to grow and absorb nutrients. If the soil is too compacted or lacks the necessary structure to support root development, it can affect the plant's health and growth. This issue can be addressed by improving soil structure through organic amendments such as compost or manure, which improve soil aeration and texture. Nutrient retention (nr) refers to the soil's ability to retain essential nutrients needed for plant growth. This concept is reinforced by various prior studies that emphasize

Table 1. Land suitability class for chili in the muara Batang Toru Sub-district, South Tapanuli Regency.

Village	Sample Location	Coordinate Point	Actual Land Suitability	Potential Land Suitability	Management Recommendations*
Muara Huta Raja	Sampling Station-01	N: 1°25′6,431″ E: 98°59′46,810″	S3.wa	S2.wa	1
	Sampling Station-03	N: 1°26′27,003″ E: 98°59′21,597″	S3.wa,rc,nr	S2.wa,rc	1.2.3
Huta Raja	Sampling Station-04	N: 1°27′13,480″ E: 98°59′15,923″	S3.wa,nr	S2.wa,nr	1,5,6
	Sampling Station-05	N: 1°27′15,992″ E: 98°59′58,516″	S3.wa,rc	S2.wa,rc	1.2.4
Bandar Hapinis	Sampling Station-06	N: 1°30′29,038″ E: 99°2′25,323″	S3.wa,nr	S2.wa,nr	1,6,9,10
	Sampling Station-07	N: 1°26′50,136″ E: 99°0′43,618″	S3.wa,rc,nr	S2.wa,rc, nr	1.4,7,8

Note: wa = water availability, rc = rooting media, nr = nutrient retention, N = North, E = East, *Management Recommendations: 1. Making beds and drainage ditches, 2. Deep soil cultivation, 3. Application of organic fertilizer (compost/manure) = 25 tons/ha/year, 4. Mulching (organic materials/plastic), 5. Provision of amendments in the form of adsorbents, such as zeolite, as much as 2 tons/ha and manure/compost 15 tons/ha/year, 6.Urea fertilization = 300 kg/ha; SP-36 = 100 kg/ha; KCl = 25 kg/ha, 7.Urea fertilization = 300 kg/ha, SP36 75 kg/ha, KCl = 25 kg/ha, 8. Providing zeolite adsorbent 1–2 tons/ha and organic fertilizer (compost and/or manure) as much as 25 tons/ha/year, 9. Giving manure/compost as much as 15 tons/ha/year and dolomite as much as 1.5 tons/ha, 10. Planting parallel to the contour and making terraces based on the width.

Table 2. Land suitability class for cucumber in the Muara Batang Toru Sub-district, South Tapanuli Regency.

Village	Sample Location	Coordinate Point	Actual Land Suitability	Potential Land Suitability	Management Recommendations*
Muara Huta Raja	Sampling Station-01	N: 1°25′6,431″ E: 98°59′46,810″	S3.wa	S2.wa	1
	Sampling Station-03	N: 1°26′27,003″ E: 98°59′21,597″	S3.wa,rc,nr	S2.wa,rc	1, 2, 3, 5
Huta Raja	Sampling Station-04	N: 1°27′13,480′ E: 98°59′15,923″	S3.wa,nr	S2.wa,nr	1, 4, 5
	Sampling Station-05	N: 1°27′15,992′ E: 98°59′58,516″	S3.wa,rc	S2.wa,rc	1, 2, 5, 6
Bandar Hapinis	Sampling Station-06	N: 1°30′29,038″ E: 99°2′25,323″	S3.wa,nr	S2.wa,nr	1, 5, 7, 8

Note: wa = water availability, rc = rooting media, nr = nutrient retention, N = North, E = East, *Management Recommendations: 1. Making beds and drainage ditches, 2. Deep soil cultivation, 3. Application of organic fertilizer (compost/manure) = 25 tons/ha/year, 4. Provision of amendments in the form of adsorbents, such as zeolite, as much as 2 tons/ha and manure/compost 15 tons/ha/year, 5.Urea fertilization = 300 kg/ha; SP-36 = 100 kg/ha; KCl = 25 kg/ha, 6.Providing zeolite adsorbent 1 tons/ha and organic fertilizer (compost and/or manure) as much as 50 tons/ha/year, 7.Giving manure/compost as much as 15 tons/ha/year and dolomite as much as 1.5 tons/ha, 8. Planting parallel to the contour and making terraces based on the width.

the importance of nutrients in supporting plant development.[3,11,12] Poor nutrient retention may lead to nutrient leaching, where important minerals and elements are washed away by rainfall or irrigation. This limitation can be mitigated by applying organic fertilizers to replenish and improve the soil's nutrient-holding capacity. To mitigate these limitations and improve land suitability, several agronomic practices can be applied, such as making beds and drainage ditches. Creating raised planting beds can improve water drainage, preventing waterlogging and ensuring plants are not waterlogged, which is crucial for chili cultivation. Additionally, drainage ditches can manage excess water and prevent root rot. Mulching by applying organic materials or plastic mulches helps retain moisture, regulate soil temperature, and reduce weed competition, which in turn supports better growth conditions for chili plants. Another improvement is the application of zeolite, which enhances soil nutrient retention by reducing leaching, thereby improving the availability of essential nutrients for plant growth. Organic fertilization can also be applied. Organic fertilizers like compost or manure (25 tons/ha/year) help enhance soil structure, improve nutrient retention, and increase microbial activity, all of which contribute to healthier soil and plants. Additionally, the use of chemical fertilizers such as Urea (300 kg/ha), SP36 (75 kg/ha), and KCl (25 kg/ha) will provide the essential nutrients needed for optimal growth. Urea is a source of nitrogen, SP36 provides phosphorus, and KCl adds potassium, which are all vital for plant development Table 1. By implementing these strategies, the marginally suitable (S3) land could be improved to a more suitable level, potentially reaching moderate suitability (S2), where the limitations are reduced, and the land can support more productive chili farming. This would ultimately result in improved yields and better overall farming outcomes for the region, so that the potential land suitability can be moderately suitable (S2).

Based on Table 2, the actual land suitability for cucumber in the three villages in the Muara Batang Toru Sub-district, South Tapanuli Regency, is classified as marginally suitable (S3) due to the limitation in water availability (wa), rooting media (rc), and nutrient retention (nr). These constraints can be addressed through several agronomic practices These constraints can be addressed through several agronomic practices,[4–6] including the construction of beds and drainage ditches, the application of 15 tons/ha/year of manure or compost, and the addition of 1.5 tons/ha of dolomite. Furthermore, fertilization with Urea (300 kg/ha), SP36 (100 kg/ha), and KCl (25 kg/ha), along with contour-based planting and terrace construction, can improve land conditions. Implementing these measures has the potential to enhance land suitability from marginally suitable (S3) to moderately suitable (S2).

Based on Table 3, the actual land suitability for shallot cultivation in the three villages of Muara Batang Toru Sub-district, South Tapanuli Regency, is classified as N1 (not currently suitable), due to limited water availability (wa). This constraint can be addressed by constructing beds and drainage ditches,[6,8] potentially improving land suitability to marginally suitable (S2).

Based on Table 4, the actual land suitability for tomatoes in the three villages in the Muara Batang Toru Sub-district, South Tapanuli Regency, is classified as marginally suitable (S3) due to limitations

Table 3. Land suitability class for shallots in the Muara Batang Toru Sub-district, South Tapanuli Regency.

Village	Sample Location	Coordinate Point	Actual Land Suitability	Potential Land Suitability	Management Recommendations*
Muara Huta Raja	Sampling Station-01	N: 1°25′6,431″ E: 98°59′46,810″			
	Sampling Station-03	N: 1°26′27,003″ E: 98°59′21,597″			
Huta Raja	Sampling Station-04	N: 1°27′13,480″ E: 98°59′15,923″			
	Sampling Station-05	N: 1°27′15,992″ E: 98°59′58,516″	N1.wa	S3.wa	1
Bandar Hapinis	Sampling Station-06	N: 1°30′29,038″ E: 99°2′25,323″			

Note: wa = water availability, N = North, E = East, *Management Recommendations: 1. Making beds and drainage ditches.

Table 4. Land suitability class for tomato in the Muara Batang Toru Sub-district, South Tapanuli Regency.

Village	Sample Location	Coordinate Point	Actual Land Suitability	Potential Land Suitability	Management Recommendations*
Muara Huta Raja	Sampling Station-01	N: 1°25′6,431″ E: 98°59′46,810″	S3.wa	S2.wa	1
	Sampling Station-03	N: 1°26′27,003″ E: 98°59′21,597″	S3.wa,rc,nr	S2.wa,rc	1, 2, 3, 5
Huta Raja	Sampling Station-04	N: 1°27′13,480″ E: 98°59′15,923″	S3.wa,nr	S2.wa,nr	1, 4, 5
	Sampling Station-05	N: 1°27′15,992″ E: 98°59′58,516″	S3.wa,rc	S2.wa,rc	1, 2
Bandar Hapinis	Sampling Station-06	N: 1°30′29,038″ E: 99°2′25,323″	S3.wa,nr	S2.wa,nr	1, 5, 6, 7

Note: wa = water availability, rc = rooting media, nr = nutrient retention, N = North, E = East, *Management Recommendations: 1. Making beds and drainage ditches, 2. Deep soil cultivation, 3. Application of organic fertilizer (compost/manure) = 25 tons/ha/year, 4. Provision of amendments in the form of adsorbents, such as zeolite, as much as 2 tons/ha and manure/compost 15 tons/ha/year, 5. Urea fertilization = 300 kg/ha; SP-36 = 100 kg/ha; KCl = 25 kg/ha, 6. Giving manure/compost as much as 15 tons/ha/year and dolomite as much as 1.5 tons/ha, 7. Planting parallel to the contour and making terraces based on the width.

in water availability (wa), rooting media (rc), and nutrient retention (nr). These constraints can be mitigated by constructing beds and drainage ditches, applying manure or compost at 15 tons/ha/year, incorporating dolomite at 1.5 tons/ha, and using fertilizers (Urea: 300 kg/ha; SP36: 100 kg/ha; KCl: 25 kg/ha). Additionally, planting parallel to the contour and implementing terracing can further improve land conditions.[4,6,15,17] With these interventions, the potential land suitability can be enhanced to moderately suitable (S2).

Based on Table 5, the actual land suitability for eggplant in the three villages in the Muara Batang Toru Sub-district, South Tapanuli Regency, is classified as marginally suitable (S3) due to limitations in water availability (wa), rooting media (rc), and nutrient retention (nr). These constraints can be mitigated by constructing beds and drainage ditches,[4,6,17] applying manure or compost at 15 tons/ha/year, incorporating dolomite at 1.5 tons/ha, and using fertilizers (Urea: 300 kg/ha; SP36: 100 kg/ha; KCl: 25 kg/ha). Additionally, planting parallel to the contour and implementing terracing can further improve land conditions.[4,17] With these interventions, the potential land suitability can be enhanced to moderately suitable (S2).

Based on Table 6, the actual land suitability for bitter melon in the three villages in the Muara Batang Toru Sub-district, South Tapanuli Regency, is classified as marginally suitable (S3) due to limitations in rooting media (rc) and nutrient retention (nr) as highlighted in several previous studies.[7,8,11,12] These constraints can be mitigated by applying manure or compost at 15 tons/ha/year and dolomite at 750 kg/ha, as well as fertilizing with Urea (250 kg/ha), SP36 (100 kg/ha), and KCl (25 kg/ha). Additionally, planting parallel to the contour and implementing terracing can further improve land conditions. With these interventions, the potential land suitability can be highly suitable in Sampling Station-01and moderately suitable (S2) in Sampling Station-03 to Sampling Station-06.

Table 5. Land suitability class for eggplant in the Muara Batang Toru Sub-district, South Tapanuli Regency.

Village	Sample Location	Coordinate Point	Actual Land Suitability	Potential Land Suitability	Management Recommendations*
Muara Huta Raja	Sampling Station-01	N: 1°25′6,431″ E: 98°59′46,810″	S3.wa	S2.wa	1
	Sampling Station-03	N: 1°26′27,003″ E: 98°59′21,597″	S3.wa,rc,nr	S2.wa,rc	1, 2, 3
Huta Raja	Sampling Station-04	N: 1°27′13,480″ E: 98°59′15,923″	S3.wa,nr	S2.wa,nr	1, 4, 5
	Sampling Station-05	N: 1°27′15,992″ E: 98°59′58,516″	S3.wa,rc	S2.wa,rc	1, 2
Bandar Hapinis	Sampling Station-06	N: 1°30′29,038″ E: 99°2′25,323″	S3.wa,nr	S2.wa,nr	1, 5, 6, 7

Note: wa = water availability, rc = rooting media, nr = nutrient retention, N = North, E = East, *Management Recommendations: 1. Making beds and drainage ditches, 2. Deep soil cultivation, 3. Application of organic fertilizer (compost/manure) = 25 tons/ha/year, 4. Provision of amendments in the form of adsorbents, such as zeolite, as much as 2 tons/ha and manure/compost 15 tons/ha/year, 5. Urea fertilization = 300 kg/ha; SP-36 = 100 kg/ha; KCl = 25 kg/ha, 6. Giving manure/compost as much as 15 tons/ha/year and dolomite as much as 1.5 tons/ha, 7. Planting parallel to the contour and making terraces based on the width.

Table 6. Land suitability class for bitter melon in the Muara Batang Toru Sub-district, South Tapanuli Regency.

Village Area	Sample location	Coordinate Point	Actual Land Suitability	Potential Land Suitability	Management Recommendations*
Muara Huta Raja	Sampling Station-01	N: 1°25′6,431″ E: 98°59′46,810	S2.nr	S1	3, 7
	Sampling Station-03	N: 1°26′27,003″ E: 98°59′21,597″	S3.nr	S2.rc	
Huta Raja	Sampling Station-04	N: 1°27′13,480″ E: 98°59′15,923″	S3.nr	S2.rc	5, 6
	Sampling Station-05	N: 1°27′15,992″ E: 98°59′58,516″	S3.rc	S2.rc	1, 2, 4
Bandar Hapinis	Sampling Station-06	N: 1°30′29,038″ E: 99°2′25,323″	S3.nr	S2.nr	8, 9, 10

Note: wa = water availability, rc = rooting media, nr = nutrient retention, N = North, E = East, *Management Recommendations: 1. Making beds and drainage ditches, 2.Provision of zeolite adsorbent as much as 1 ton/ha, 3.Application of organic fertilizer (compost/manure) = 25 tons/ha/year, 4. Provision of organic materials (compost/manure), 5. Provision of amendments in the form of adsorbents, such as zeolite, as much as 2 tons/ha, 6. Urea fertilization = 300 kg/ha; SP-36 = 100 kg/ha; KCl = 25 kg/ha, 7.Urea fertilization = 300 kg/ha; SP-36 = 50 kg/ha; KCl = 25 kg/ha., 8. Application of manure/compost as much as 15 tons/ha/year and dolomite as much as 750 kg/ha, 9. Fertilization Urea = 250 kg/ha; SP36 = 100 kg/ha; KCl = 25 kg/ha., 10. Planting parallel to the contour and making terraces based on the width.

The cost analysis for transitioning actual land suitability to potential suitability, as detailed in Tables Tables 1 to 6, is calculated based on current prices and an exchange rate of approximately 1 USD=16,246 IDR. The costs are as follows: Urea fertilizer at IDR 6,000/kg (USD 0.37), SP36 at IDR 2,000/kg (USD 0.12), KCl at IDR 10,000/kg (USD 0.62), ridge construction at IDR 3,000/m (USD 0.18), and drainage ditch construction at IDR 6,000/m (USD 0.37).

The results of the land evaluation analysis presented in Tables 1 to 6 indicate that the potential commercial vegetable crops suitable for development in this area include red chili, red onion, cucumber, tomato, bitter melon, and eggplant. Although the actual land suitability class is predominantly marginally suitable (S3), with some areas currently not suitable (N1) Table 3 due to excess water availability from high rainfall, the potential land suitability class can generally be improved to moderately suitable (S2), with certain areas even reaching highly suitable (S1) Table 6. This water excess constraint can be mitigated through the construction of drainage ditches[4,6] and ridges/beds, as recommended in the management strategies outlined in Table 1.

Another major constraint affecting vegetable crops' growth and production is limited nutrient retention, especially low organic matter content and nutrient availability, especially N, P, and K. However, these constraints can be effectively addressed through the application of mulch, organic fertilizers such as compost or manure, and artificial fertilizers at the recommended dosage, as presented in the management recommendations Table 1. By implementing these measures, commercial vegetable cultivation in this area can be developed sustainably.[17]

Polyculture planting systems, especially intercropping and rotational cropping, contribute to a sustainable agricultural system by providing multiple benefits. These systems allow for continuous crop yields in accordance with seasonal fruiting patterns (economic aspect), help regulate the prices of essential commodities in rural areas (social aspect), and mitigate soil erosion by maintaining continuous vegetation cover or mulch (environmental aspect).

The provision of artificial fertilizers such as Urea, SP-36, and KCl, as outlined in the management recommendations Table 1, can be reduced by incorporating organic fertilizers, including mulch from decomposed plant residues, compost, and manure.[15,17] Managing organic material from previous planting residues by burying it in drainage ditches using vertical mulch techniques will help improve the physical, chemical, and biological fertility of the soil, indicated by a soil structure that is increasingly loose and remains moist even in the dry season.

Mapping of actual and potential land suitability classes

Actual and potential land suitability maps for red chilies, cucumbers, shallots, tomatoes, eggplants, and bitter melon are presented in Figs. 2 to 7.

The maps Figs. 1 to 6 are essential tools for farmers and land planners, providing insight into areas where seasonal crops can be successfully cultivated (actual suitability) and where improvements can be made (potential suitability). Understanding both actual and potential suitability helps prioritize interventions such as soil enhancement and irrigation improvements to increase productivity and ensure long-term sustainability. Additionally, these maps offer a comprehensive overview of the land's current

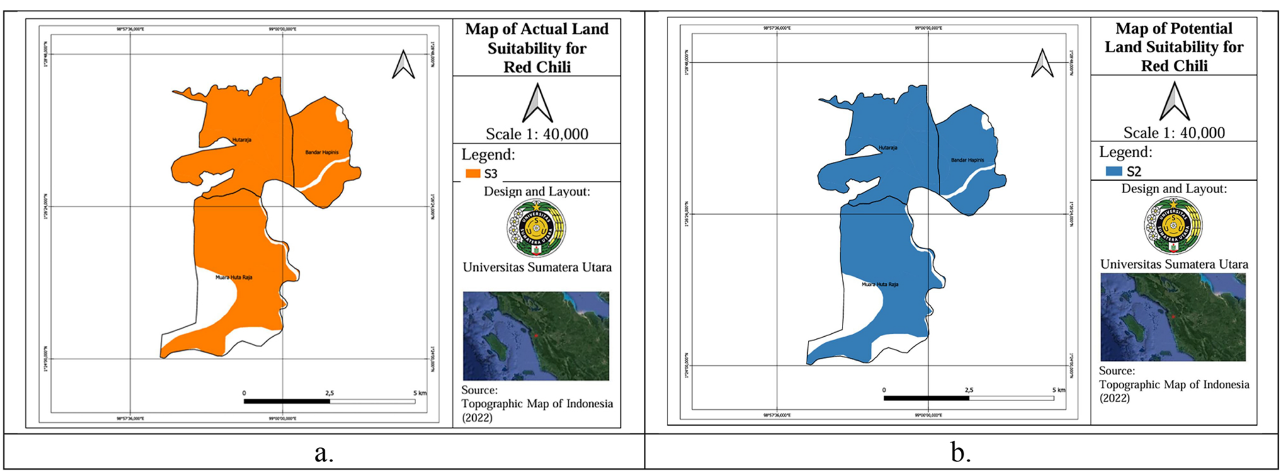

Fig. 2. Land suitability map for Red chili: a. actual, b. potential.

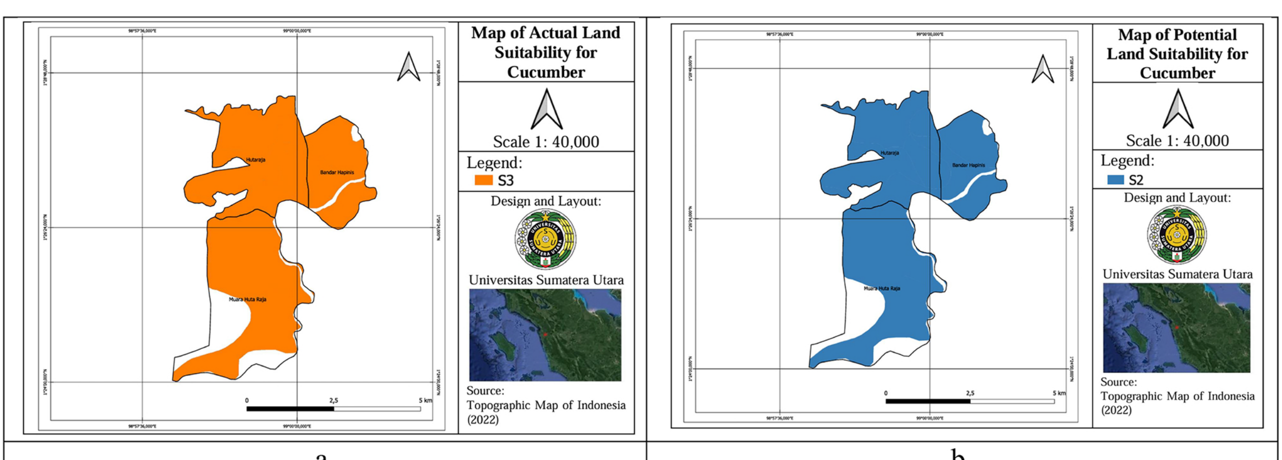

Fig. 3. Land suitability map for Cucumber: a. actual, b. potential.

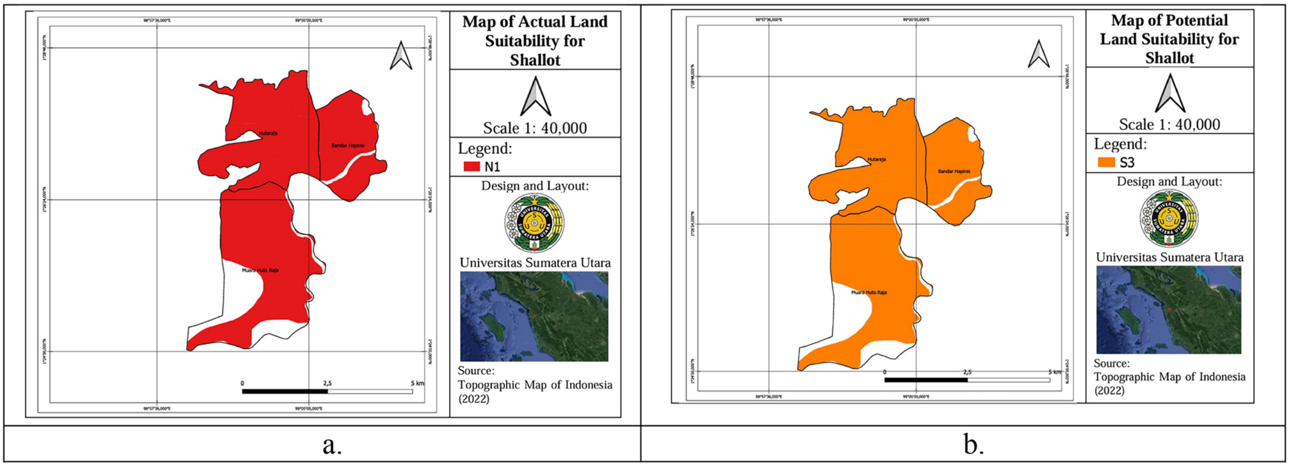

Fig. 4. Land suitability map for shallot: a. actual, b. potential.

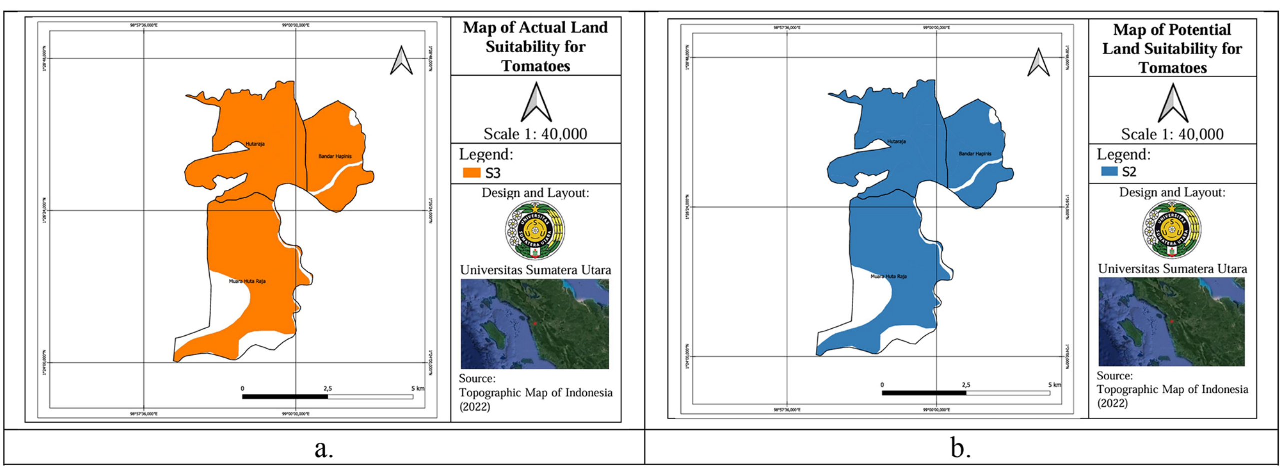

Fig. 5. Land suitability map for Tomatoes: a. actual, b. potential.

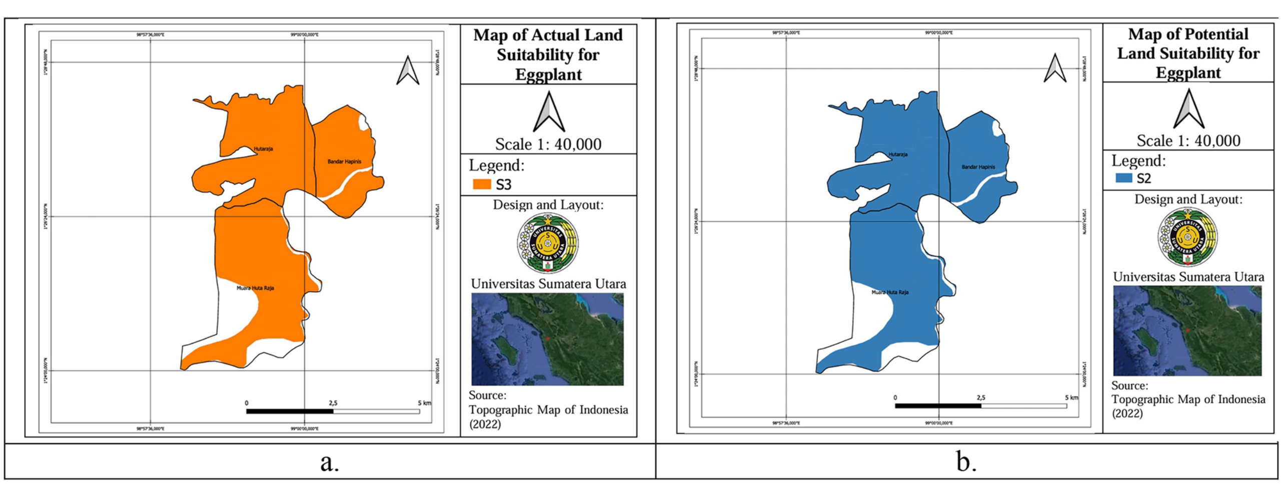

Fig. 6. Land suitability map for Eggplant: a. actual, b. potential

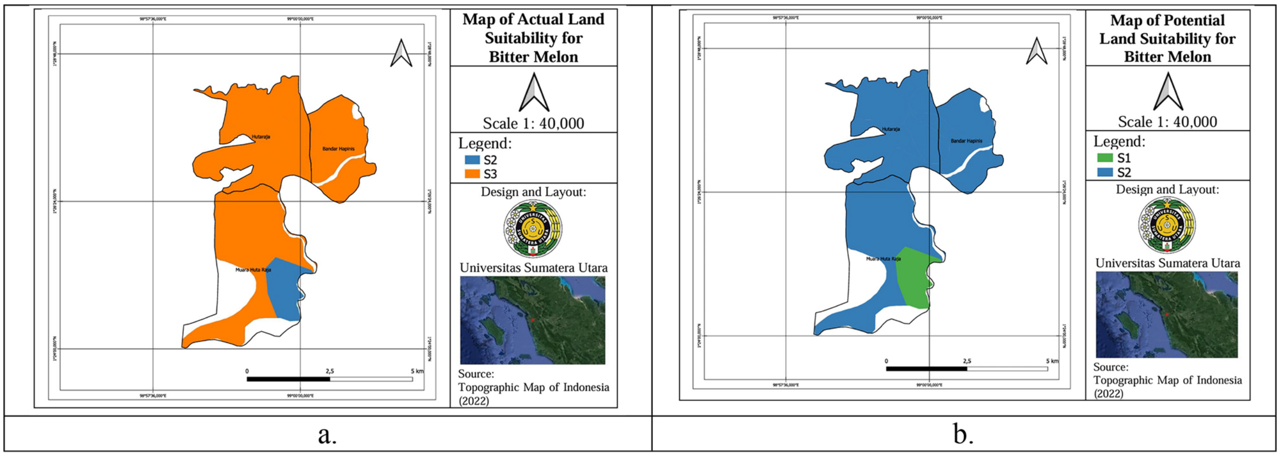

Fig. 7. Land suitability map for Bitter melon: a. actual, b. potential

and future capabilities for seasonal plant cultivation. By identifying limitations and applying corrective measures, land suitability can be enhanced, leading to higher yields and more efficient agricultural practices. The actual and potential land suitability maps serve as valuable decision-making tools, enabling farmers to maximize land use, minimize risks, and optimize resource use.[15,17] Furthermore, these maps support data-driven decision-making, helping farmers improve yields, reduce costs, and promote sustainable agricultural practice.

Support for SDGs

The results of this research support the achievement of the SDGs, as explained before, there are 17 SDGs.[26] In this case, very related, especially the goals:

1. Supporting Food Security (SDG 2. Zero Hunger and SDG 15. Life on Land)

Muara Batang Toru Sub-district has great potential for productive vegetable farming. Understanding land suitability for crops such as red chili, cucumber, shallot, tomato, eggplant, and bitter melon enables the optimization of production to meet local food demands and wider market needs. Determining land-limiting factors allows farmers to maximize yields through appropriate management practices and technology, as agreed with previous studies. Identifying land-limiting factors enables farmers to optimize crop yields by implementing suitable management practices and utilizing appropriate technologies, as supported by previous studies.[27–29] Balancing productivity (SDG 2) and ecosystem conservation (SDG 15) can be achieved through sustainable intensification and conservation-based strategies. Key approaches include the application of precision agriculture to optimize resource use, addressing land-limiting factors such as soil fertility and erosion through techniques such as agroforestry, and implementing GIS-based land-use zoning to allocate areas for agriculture and conservation. Integration of climate-smart agriculture, such as the use of drought-resistant varieties and efficient irrigation, increases resilience while reducing environmental impacts. Farmer education and incentives for environmentally friendly practices, coupled with partnerships between stakeholders, ensure sustainable production. Regular monitoring of environmental indicators and the implementation of agroforestry systems further align agricultural productivity with ecosystem health, supporting long-term sustainability.

2. Improving Farmer Welfare (SDG 1. No Poverty and SDG 8. Decent Work and Economic Growth)

This research provides recommendations for land management to optimize crop yields. Increased productivity will directly impact farmers' income, reduce poverty, and create new economic opportunities, as agreed with previous studies. Enhanced productivity will have a direct positive effect on farmers' income, help alleviate poverty, and open up new economic opportunities, as confirmed by previous studies.[28,30] Diversification of appropriate crop types increases economic value and competitiveness.

3. Sustainable Land Management (SDG 12. Responsible Consumption and Production and SDG 15. Life on Land)

This study identifies land-limiting factors, such as soil fertility, water availability, and climate conditions, to optimize the efficient and environmentally friendly use of agricultural inputs such as fertilizers and pesticides, as mentioned before by a previous study.[29]

The proposed land management recommendations promote sustainable agricultural practices, ensuring long-term soil quality and ecosystem preservation.

4. Adaptation to Climate Change (SDG 13. Climate Action)

With changing climate patterns affecting agricultural productivity, this research is crucial in providing land use guidelines that align with current environmental conditions. Implementing these guidelines will enhance farmers' resilience to crop failure risk due to climate change, as agreed with previous studies. Applying these guidelines will strengthen farmers' ability to cope with the risk of crop failures caused by climate change, as supported by previous studies.[29]

5. Optimizing Regional Planning (SDG 11. Sustainable Cities and Communities)

Land suitability research supports local governments in developing spatial planning based on regional potential. Identifying Muara Batang Toru Sub-district as a vegetable production center area can attract investment in the agricultural sector, as mentioned before in a previous study.[29,30]

6. Contribution to Increasing Local and National Production

Crops such as red chili, tomatoes, and shallots are in high demand in both local and national markets. Optimizing land suitability in Muara Batang Toru Sub-district can enhance the production of these strategic commodities, reduce reliance on external supplies, and contribute to price stability.

7. Empowering Local Farmers

The findings of this study can serve as a foundation for training and mentoring local farmers on crop selection, optimal farming techniques, and effective land management, thereby enhancing the empowerment of farming communities.

Thus, this research not only has academic significance but also makes a tangible contribution to sustainable development in South Tapanuli Regency, especially in supporting the achievement of the SDGs.

The findings are expected to provide technical recommendations to increase land productivity, promote agricultural sustainability, and encourage the socio-economic stability of local communities, ultimately supporting sustainable agricultural production and the achievement of SDG targets in the Muara Batang Toru Sub-district. However, adopting sustainable farming practices is often hindered by factors such as farmers' lack of knowledge, limited access to resources like capital and technology, and resistance to change. In addition, inadequate infrastructure, uncertain climate challenges, unsupportive policies, and a lack of market incentives pose significant barriers. To overcome these challenges, a comprehensive approach is essential, involving intensive training and extension services, financial assistance through subsidies and microcredit, infrastructure development, supportive policy implementation, and the creation of markets for environmentally friendly products. By applying this integrated strategy, the adoption of sustainable practices can be enhanced, ensuring long-term success in increasing productivity while preserving the environment.

Conclusion

Commodities such as red chili, tomatoes, and bitter melon have significant potential for productivity improvement through simple interventions. Implementing intercropping and crop rotation systems can optimize yields while maintaining environmental sustainability, enhancing agricultural output, and encouraging the socio-economic stability of the community in Muara Batang Toru Sub-district.

For practical application of these findings, it is recommended that farmers participate in training programs that focus on sustainable agricultural techniques and utilize support from agricultural extension services to integrate advanced technologies and optimize resource use. In addition, the government can support by providing subsidies for environmentally friendly inputs, expanding market access for farmers, and integrating land suitability data into regional planning frameworks. In addition, nationally, the implementation of GIS-based land use zoning and monitoring systems can improve local decision-making and ensure land use is aligned with sustainable goals.

Further research is needed to explore the long-term impacts of the proposed practices on soil health, biodiversity, and economic resilience. Additionally, research could explore the integration of precision and climate-smart agricultural technologies tailored to the unique conditions of the region. This research is aligned with and directly contributes to the achievement of several Sustainable Development Goals (SDGs), including No Hunger, No Poverty, and Responsible Consumption and Production.

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Authors' declaration

- Conflict of interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images that are not ours have been included with the necessary permission for re-publication, which is attached to the manuscript. Besides, the Figures and images, which are not ours, have been given permission for republication attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at Universitas Sumatera Utara (USU).

Authors' contribution statement

R., A.R., T.A.A., and R.H.H. contributed to the study design, data analysis, drafting, and manuscript editing. C.P., R.S., M.A., N.W., and A.H.O.S. contributed to the design, sampling, data collection, data entry, preparation, and editing of the manuscript. S.G. and M.H.I contributed to editing the latest manuscript.

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ملاءمة الأراضي للمحاصيل الموسمية: العوامل المقيِّدة واستراتيجيات الإدارة المتوائمة مع أهداف التنمية المستدامة(SDGs)

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الملخص

تُعدّ دراسة تقييم الأراضي في منطقة موارا باتانغ تورو الفرعية ضرورية لتحديد إمكانات تطوير المحاصيل الموسمية فيها. تهدف هذه الدراسة إلى تقييم ملاءمة الأراضي لستة محاصيل موسمية، تشمل الفلفل الأحمر، والخيار، والبصل الأحمر، والطماطم، والباذنجان، والقرع المر، في منطقة موارا باتانغ تورو، محافظة تابانولي الجنوبية. اعتمدت الدراسة منهج المسح، من خلال دمج المشاهدات الحقلية والتحليل المخبري وفق معايير محددة مسبقًا تستند إلى مزيج من المعايير العالمية المعتمدة والظروف المحلية. كما استُخدمت نُظم المعلومات الجغرافية لرسم خرائط درجات الملاءمة الأرضية الحالية والمحتملة للمحاصيل الخضرية. تشير النتائج إلى أن معظم درجات الملاءمة الأرضية الحالية تقع ضمن الفئة المناسبة بدرجة هامشية (S3) أو غير المناسبة حاليًا(N1) ، ويُعزى ذلك أساسًا إلى عوامل مقيِّدة مثل: توفر المياه(wa) ، وانخفاض الاحتفاظ بالعناصر الغذائية(nr) ، ورداءة وسط التجذير(rc) ، وارتفاع معدّل الأمطار .(tc) ويمكن لممارسات الإدارة الجيدة—مثل إنشاء أنظمة الصرف والأسِرّة المرتفعة، وتطبيق 15–25 طنًا من الأسمدة العضوية للهكتار سنويًا، وإضافة الجير أو الدولوميت—تحسين درجة الملاءمة الأرضية إلى مناسبة بدرجة معتدلة (S2) أو حتى مناسبة بدرجة عالية .(S1)وتُعدّ محاصيل مثل الفلفل الأحمر والطماطم والقرع المر من السلع الزراعية التي تمتلك إمكانية كبيرة لزيادة الإنتاجية مع هذه التدخلات. كما توصي الدراسة بتطبيق أنظمة الزراعة البينية وتدوير المحاصيل لتحقيق أفضل غلة، والحفاظ على الاستدامة البيئية، وتعزيز الإنتاج الزراعي، ودعم الاستقرار الاجتماعي والاقتصادي في منطقة موارا باتانغ تورو. وتُسهم هذه الدراسة أيضًا في تحقيق أهداف التنمية المستدامة (SDGs).

الكلمات المفتاحية: ملاءمة عالية، إدارة الأراضي، العوامل المقيّدة، الاحتفاظ بالعناصر الغذائية، أهداف التنمية المستدامة، (SDGs).