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Spatial Analysis of Land Suitability for Livestock Farming in East Java Using GIS and DEM-Based Environmental Modeling

Agus Susilo[1*], Muhammad Halim Natsir[1], Kuswati[1], Tri Eko Susilorini[1], Novandi Rizky Prasetya[2]

[1] Faculty of Animal Science, Universitas Brawijaya, Malang 65145, Indonesia
[2] Department of Agricultural Science, Faculty of Agriculture, Universitas Brawijaya, Malang 65145, Indonesia

Corresponding Author Email: agussusilo@ub.ac.id

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ABSTRACT

Livestock farming in Indonesia is highly influenced by environmental factors such as temperature, oxygen levels, and slope, which affect productivity and sustainability. This study employs Geographic Information System (GIS) and Digital Elevation Model (DEM) data to assess land suitability for dairy cattle, beef cattle, chicken, and quail farming in East Java. Temperature was estimated using Braak's formula, while oxygen levels were modeled based on Peacock's equation, and slope classification was performed using ArcGIS tools. Subsequently, each parameter was classified based on specific physiological thresholds for each livestock type: temperature for cattle, oxygen levels for poultry, and slope for general farm construction. The land suitability classification was validated through expert consultation. The results indicate that optimal temperatures for dairy cattle (18–24℃) and beef cattle (20–26℃) are found in mid-altitude regions, whereas highland areas with lower temperatures are less suitable. Poultry farming was most viable in areas with oxygen levels between 18–20.8%, while slopes exceeding 40% posed significant operational challenges for large-scale livestock farming. This study underscores the importance of integrating spatial analysis in precision livestock planning to optimize land use and sustainable management. The findings provide a scientific basis for zoning regulations, infrastructure investment, and sustainable livestock management strategies.

1. INTRODUCTION

The livestock sector plays a crucial role in ensuring global food security and contributes significantly to national economies, particularly in Indonesia. However, one of the primary challenges in livestock farming is determining optimal locations by considering environmental factors such as temperature, oxygen levels, and land slope, all of which influence livestock productivity. While the foundational importance of these factors is well-established in animal environmental physiology, their integration into practical, high-resolution spatial planning for livestock farming remains a critical gap, especially in the Indonesian context. Previous studies have demonstrated that proper land selection can enhance production efficiency and animal welfare. However, existing research in Indonesia has three key shortcomings: first, a predominant focus on land suitability for agriculture rather than livestock farming; second, a tendency to consider environmental factors in isolation rather than in an integrated multi-parameter assessment; and third, a lack of explicit, high-precision spatial modeling that generates actionable maps for specific livestock species. The advancement of mapping technologies using Geographic Information Systems (GIS) and Digital Elevation Models (DEM) now enables such precise analyses. Therefore, to address these gaps, this study aims to generate explicit, high-resolution land suitability maps for four major livestock species (dairy cattle, beef cattle, chickens, and quails) in East Java Province by integrating GIS with physiological thresholds for temperature, oxygen, and slope.

Recent studies have increasingly highlighted the convergence of spatial analysis and animal physiology in agricultural planning. For instance, research on the spatial layout of livestock farming has demonstrated that integrating GIS with environmental parameters can significantly improve site-selection outcomes [1, 2]. This is supported by Mushawwir et al. [3], who specifically quantified the impact of altitude-derived temperature and oxygen variations on poultry productivity, underscoring the critical link between animal physiology and geospatial data. Furthermore, Wang et al. [4], in their study on remote sensing applications for species distribution modeling, emphasized that integrating topographic, temperature, and other environmental data is key to ensuring livestock sector sustainability. The methodological approach is reinforced by studies like Taghizadeh-Mehrjardi et al. [5], who applied machine learning models for land suitability analysis and revealed that environmental factors such as elevation and temperature strongly determine land productivity. These studies collectively establish a robust foundation for the GIS-based multi-criteria classification approach employed in this work. Considering these advancements, our study leverages DEM data and physiological models to develop a species-specific land suitability mapping model for livestock farming in East Java.

This study has two primary objectives: first, to generate explicit spatial land suitability maps for four major livestock species (dairy cows, beef cattle, chickens, and quails) in East Java Province by classifying and integrating key environmental parameters of temperature, oxygen levels, and slope; and second, to quantify the spatial distribution of suitable areas in order to provide a scientific basis for regional land use planning and zoning regulations. The main contribution of this research is the development of a practical, GIS-based spatial model that bridges the fields of animal environmental physiology and spatial planning, which can serve as a direct reference for livestock zoning in Indonesia. Thus, this study not only offers academic insights but also actionable, data-driven recommendations for farmers and policymakers to optimize land use for sustainable livestock farming.

2. MATERIALS AND METHODS

2.1 Study area

This study was conducted in East Java Province, which was selected due to its status as one of the regions with the largest livestock population in Indonesia, based on data from Statistics Indonesia [6]. Moreover, East Java exhibits diverse topographical and climatic conditions, with elevations ranging from 0 m a.s.l. in coastal areas to 3,669 m a.s.l. at its highest volcanic peaks, making it an ideal location for analyzing land suitability for cattle farming, as shown in Figure 1. The province is geographically positioned between 111°0' and 114°4' East Longitude and 7°12' and 8°48' South Latitude. According to the Schmidt-Ferguson climate classification, the region is predominantly categorized under climate types C and D, indicating moderate to relatively dry rainfall conditions. Meanwhile, based on the Köppen climate classification, most of East Java falls under the Aw type (tropical with a distinct dry season).

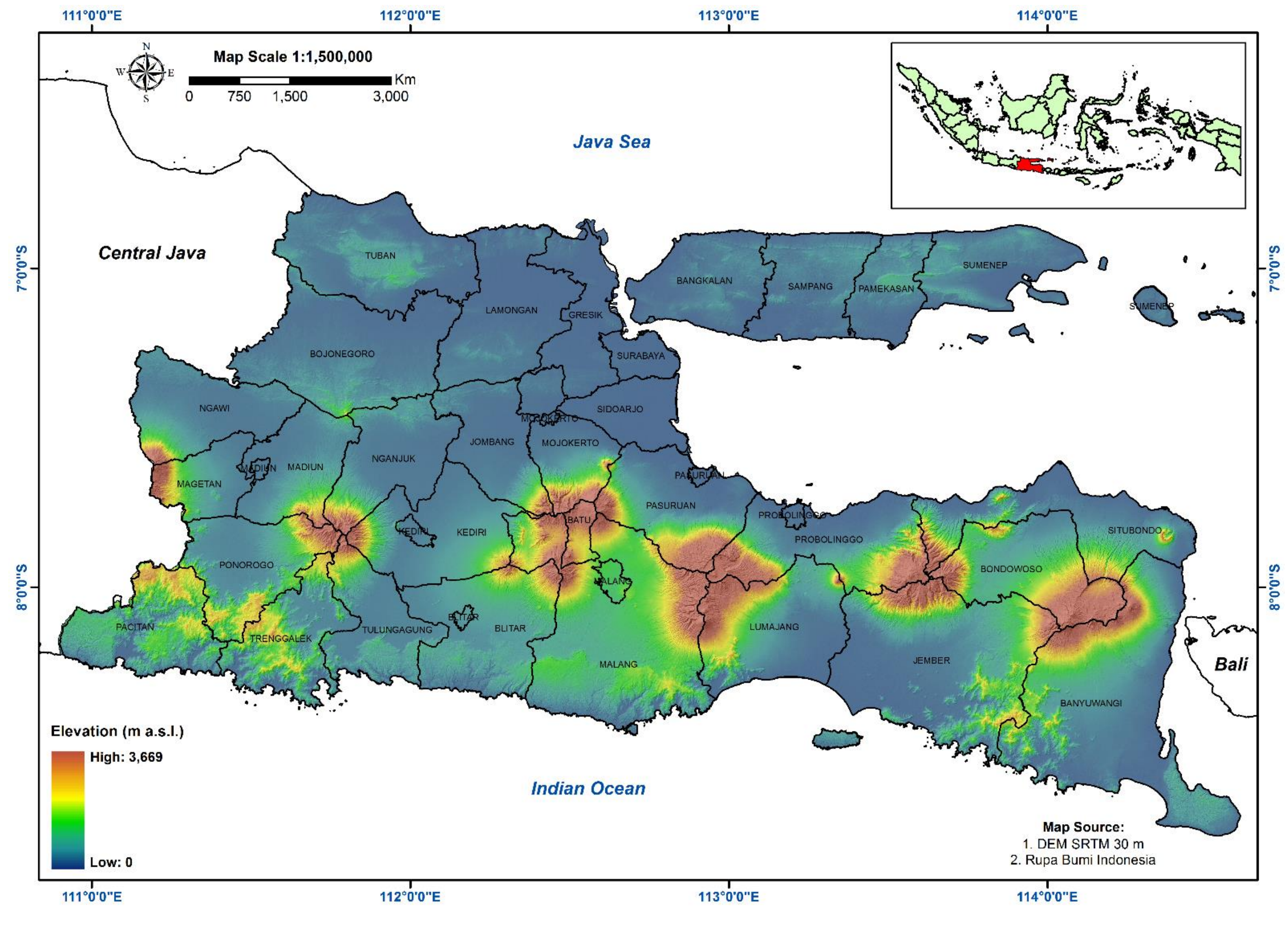

Figure 1. Study area

East Java comprises 29 regencies and 9 cities. The northern coastal region includes Tuban, Lamongan, Gresik, Sidoarjo, Probolinggo, and Situbondo, while the southern coastal region encompasses Pacitan, Trenggalek, Tulungagung, Blitar, Malang, Lumajang, and Banyuwangi. Additionally, East Java is home to several active and inactive volcanoes, including Mount Semeru, Mount Bromo, Mount Arjuno, Mount Wilis, and Mount Kelud. The presence of these volcanoes creates diverse topographical features and soil conditions, influencing land suitability for livestock farming.

2.2 Data collection

This study integrates Digital Elevation Model (DEM), temperature, and oxygen level data to conduct a livestock land suitability analysis in East Java Province. Data were collected and processed using a Geographic Information System (GIS) approach and environmental modeling techniques to ensure more accurate results that can serve as a reference for data-driven livestock planning. Previous studies have demonstrated that using DEM in topographic mapping provides more precise results in land suitability analysis compared to traditional methods [7], while predictive models for temperature and oxygen have been applied in various spatially-based environmental mapping studies [5, 8].

The DEM data used in this study were obtained from the Shuttle Radar Topography Mission (SRTM) with a 30-meter spatial resolution. These data were sourced from the USGS Earth Explorer platform, which provides access to various types of remote sensing data, including topographic information necessary for spatial analysis. DEM data processing was conducted using ArcGIS software, where elevation and land slope were extracted using the Slope Analyst tool. The slope data were then classified into multiple suitability categories based on threshold values relevant to livestock operations. This classification is essential since land with slopes greater than 40% presents significant operational challenges, especially for large-scale livestock farming [9].

Environmental temperature was estimated using Braak's equation [10], which states that every 100-meter increase in elevation results in a temperature decrease of approximately 0.6℃. Temperature analysis was performed using ArcGIS Spatial Analyst Tools to generate an elevation-based temperature distribution map. This model enables the identification of land suitability zones based on optimal temperature ranges for different livestock types, such as dairy cattle (18–24℃) and beef cattle (20–26℃) [8]. Furthermore, oxygen levels were calculated based on Peacock's method [11], which explains the relationship between altitude and atmospheric oxygen concentration. As elevation increases, atmospheric pressure decreases, leading to a reduction in available oxygen for living organisms. Oxygen distribution mapping was conducted using the Raster Calculator tool in ArcGIS, and the results were correlated with other parameters to assess their impact on livestock land suitability. Areas with oxygen levels below 18% were classified as unsuitable for poultry farming, considering the risk of hypoxia in chickens and quails [5].

2.3 Analytical techniques

The collected data were analyzed using a combination of spatial analysis and classification techniques. First, a classification scheme was applied to each environmental parameter based on established physiological thresholds for each livestock type. This involved categorizing temperature for cattle, oxygen levels for poultry, and slope for general farm construction, as validated through expert consultation. The relationship between elevation, temperature, and oxygen levels was examined during the data preprocessing stage using linear regression analysis and Pearson correlation. However, the core of our spatial modeling relied on this direct classification approach rather than a weighted overlay, ensuring clarity and transparency in the suitability criteria.

The methodology implemented in this study ensures the accuracy of livestock land suitability mapping in East Java Province. By integrating GIS, DEM, and physiology-based classification models, this study provides new insights into optimal livestock zoning. The findings contribute to data-driven land-use policy development and serve as a reference for the livestock industry to improve production efficiency through scientifically informed location planning.

Based on the conducted analysis, the systematic evaluation of each parameter is based on the relative importance of each variable in assessing land feasibility for livestock farming. It has been widely used in previous studies to evaluate GIS-based land suitability, such as Peng et al. [1], who applied a similar classification approach to assess land suitability for livestock. Moreover, this method is commonly used in DEM-based land suitability mapping and other environmental factors. The study by Wang et al. [4] highlights the importance of integrating topographic, temperature, and other environmental data into species distribution models relevant to the livestock sector. Similarly, Taghizadeh-Mehrjardi et al. [5] found that utilizing this technique in spatial mapping systems significantly improves the clarity and applicability of land suitability predictions compared to more complex methods.

The selection of temperature, oxygen levels, and land slope in this study is based on the significant impact of these factors on livestock land suitability. Temperature is a key climatic factor influencing livestock health and productivity. High ambient temperatures can cause heat stress, negatively affecting feed intake and livestock performance [12]. Oxygen levels are directly related to land elevation, where increased elevation leads to lower atmospheric pressure and reduced oxygen availability. Hypoxia conditions due to low oxygen levels can impact livestock metabolism and health, making it essential to consider this factor in land suitability evaluations [13]. Land slope is also crucial in determining accessibility and erosion risk in livestock farming areas. Steeper slopes are associated with higher erosion risks and can present operational difficulties in livestock activities. Slope is often included as a primary parameter in land suitability assessments for various land-use applications, including livestock farming [9].

2.4 Data processing

2.4.1 Air temperature analysis

Environmental temperature was estimated using Braak's equation [10], which provides a standard lapse rate for temperature changes with elevation. According to this equation, air temperature decreases by approximately 0.6℃ for every 100 m increase in altitude. This principle was applied in the present study using the following formula:

$$t = 26.3℃ - \frac{(0.61℃ \times h)}{100} \tag{1}$$

where, t represents air temperature, and h denotes elevation obtained from DEM data. Temperature analysis was conducted using Spatial Analyst Tools in ArcGIS software to generate an elevation-based temperature distribution map. This model enables the identification of land suitability zones based on optimal temperature ranges for different livestock types, such as dairy cattle (18–24℃) and beef cattle (20–26℃).

2.4.2 Oxygen concentration analysis

Oxygen concentration was estimated using the method proposed by Peacock [11], which establishes the relationship between altitude and atmospheric oxygen availability. With increasing elevation, atmospheric pressure declines, thereby reducing the partial pressure of oxygen and the amount accessible to living organisms. This relationship was quantified in the present study using the following equation:

$$O_2 = O_{2.0} \times e^{\frac{-h}{H}} \tag{2}$$

where, O_2 is the oxygen concentration at a given elevation, $O_{2.0}$ represents the sea-level oxygen concentration (~20.9%), h is the altitude (in meters), and H is the atmospheric scale height (~7,000 meters).

2.4.3 Land slope analysis

Land slope was calculated using the Slope Analyst tool in ArcGIS software, which applies Horne's method to estimate surface gradients based on elevation data from the Digital Elevation Model (DEM). This method utilizes the elevation values from a target cell and its eight neighboring cells to compute partial derivatives in the x and y directions, which are then used to determine land slope [14]. The resulting slope values were classified into various land suitability levels for livestock farming, considering slope thresholds relevant to livestock operations. Land with a slope exceeding 40% poses significant operational challenges, particularly for large-scale livestock farming [15].

2.5 Land suitability assessment

2.5.1 Land suitability for dairy and beef cattle

Temperature is a key environmental factor influencing livestock productivity, particularly for dairy and beef cattle. Variations in ambient temperature can significantly affect animal metabolism, feed efficiency, and overall health [16]. Dairy cattle, for instance, are highly sensitive to heat stress, which can reduce milk production and reproductive performance. Similarly, beef cattle require an optimal temperature range to maintain efficient weight gain and meat quality. The classification of land suitability based on temperature conditions provides a scientific basis for determining the optimal locations for dairy and beef cattle farming, as shown in Table 1.

Table 1. Land suitability for dairy and beef cattle based on temperature

Livestock Type	Temperature (°C)	Category	Description
Dairy Cattle	< 18	Low	Not ideal
	18–24	Optimal	Ideal
	> 24	High	Not ideal
Beef Cattle	< 20	Low	Not ideal
	20–26	Optimal	Ideal
	> 26	High	Not ideal

Table 2. Land suitability for dairy and beef cattle based on temperature

Poultry Type	Oxygen (%)	Category	Description
Chickens & Quails	< 15	Very Low	Severe Hypoxia
	15–17.9	Low	Not Ideal
	18–20.8	Moderate	Acceptable
	> 24	High	Optimal

2.5.2 Land suitability for chicken and quail

Oxygen availability is a crucial factor influencing the productivity and health of poultry, including chickens and quails [17]. Low oxygen levels can lead to hypoxia, which negatively affects respiratory efficiency, feed conversion rates, and overall growth performance. Poultry raised in areas with insufficient oxygen concentrations may experience increased stress levels, reduced egg production, and higher mortality rates. Classifying land suitability based on oxygen concentration is essential for optimizing poultry farm locations, as shown in Table 2.

3. RESULTS

3.1 Spatial distribution of air temperature

The spatial distribution analysis of air temperature in East Java Province revealed a temperature range between 3.92°C and 26.61°C (Figure 2). Lower temperatures were predominantly observed in high-elevation areas, particularly in mountainous regions such as Mount Semeru, Mount Arjuno, Mount Bromo, and Mount Wilis. This finding aligns with the principle of temperature decrease with elevation, where higher altitudes generally experience lower temperatures. Conversely, lowland and coastal areas, including the northern coastal regions of Tuban and Lamongan, as well as southern areas like Banyuwangi, exhibited higher temperatures closer to the upper range.

This temperature variation is influenced by complex topographical factors and differing airflow distributions across regions, making it a critical determinant in mapping land suitability for livestock farming in the province. A deeper analysis of the spatial pattern reveals that the optimal temperature zones for livestock do not form random patches but are organized in a distinct, contiguous band running along the mid-altitude slopes of the province's major volcanic arcs. This band is particularly evident along the slopes connecting the Tengger Massif (Bromo) to the Semeru complex in the east, and the Arjuno-Welirang complex to the Wilis plateau in the west. The contiguity of this zone is a direct function of the region's geology, where the consistent elevation provided by these ancient volcanic formations creates a stable, cool microclimate, shielded from the extreme heat of the lowlands and the cold of the highest peaks. Understanding these spatial temperature variations is essential for identifying optimal locations for different livestock types, ensuring sustainable and efficient livestock management in East Java.

3.2 Spatial distribution of oxygen concentration analysis

The spatial distribution analysis of oxygen concentration in East Java Province revealed a range between 13.85% and 19.62% (Figure 3). Lower oxygen levels were predominantly found in high-altitude regions, particularly around Mount Semeru, Mount Bromo, Mount Arjuno, and the Ijen Mountains. This phenomenon aligns with the principle that as elevation increases, atmospheric pressure decreases, leading to a lower concentration of oxygen molecules per unit volume of air.

Conversely, lowland and coastal areas, such as the northern coastal regions of Gresik, Lamongan, and Probolinggo, exhibited higher oxygen levels approaching the upper threshold. The spatial pattern of oxygen concentration is intrinsically linked to the topography, mirroring the elevation model. However, a critical finding is that the 'moderate' oxygen class (18–19.62%), deemed suitable for poultry, covers the vast majority of the province's area. This suggests that from an oxygen perspective alone, poultry farming is viable across most of East Java, excluding the extremely highlands. The spatial distribution of less suitable, low-oxygen areas is highly fragmented and confined to the peaks and upper slopes of the major mountains, indicating that the economic impact of oxygen limitation on the poultry industry is geographically concentrated rather than widespread.

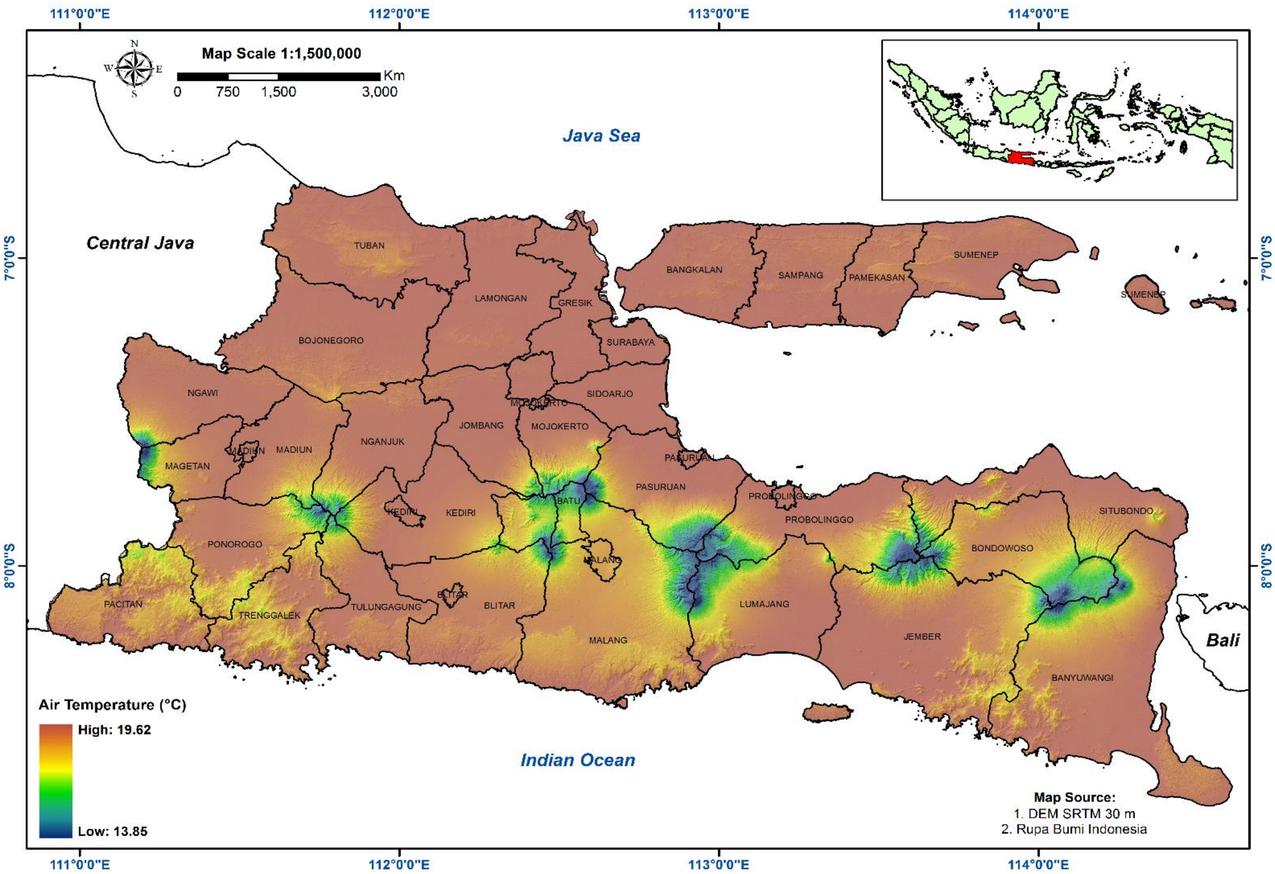

Figure 2. Spatial distribution of air temperature in the study area

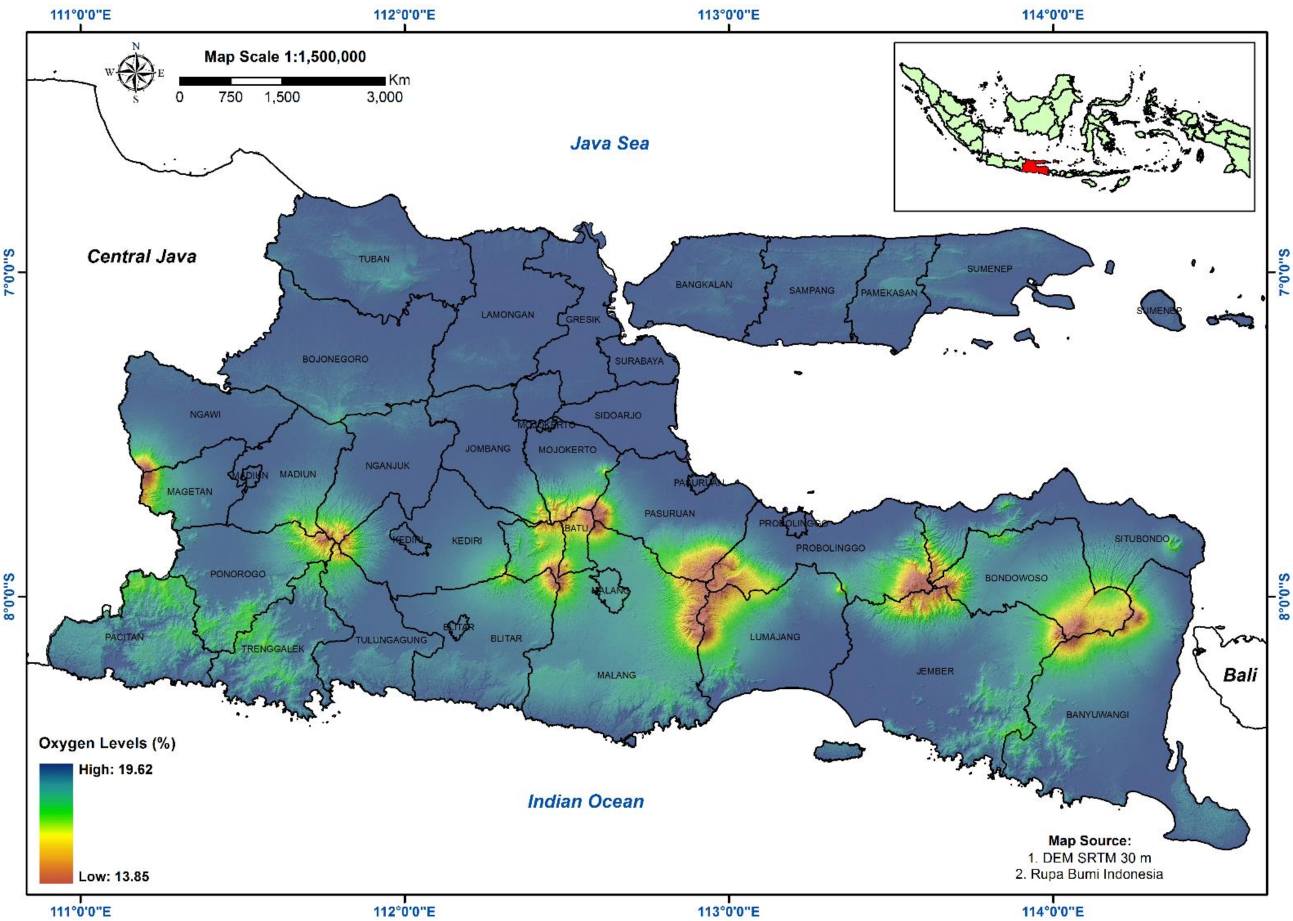

Figure 3. Spatial distribution of oxygen concentration in the study area

3.3 Spatial distribution of land slope

The spatial distribution analysis of land slope in East Java Province identified seven slope classes, categorized as 0–3%, 3–8%, 8–15%, 15–25%, 25–40%, 40–60%, and >60%. Low-slope areas (0–3%) are predominantly found in lowland regions, particularly in northern coastal areas such as Lamongan, Tuban, and Gresik, as well as in agricultural zones in Madiun and Bojonegoro. Conversely, high-slope areas (> 25%) dominate the mountainous regions, including Mount Semeru, Mount Arjuno, Mount Wilis, and the Ijen Mountains. Additionally, the southern mountain range stretching from Pacitan to Banyuwangi exhibits steep topography, with some locations exceeding 60% slope inclination (Figure 4).

The spatial pattern of slope suitability reveals a fundamental challenge for large-scale livestock farm construction. The most suitable flats to gentle slopes (0–8%) are predominantly located in the northern coastal plain and several large, low-lying inland basins. These areas are often prime agricultural land and are in close proximity to major population and economic centers like Surabaya, Gresik, and Sidoarjo. This creates potential land-use conflict between urban expansion, high-value agriculture, and livestock farming. Conversely, the extensive steep areas in the south and central highlands, while less contested, present high development costs. A significant finding is the presence of a 'slope suitability corridor'—areas with slopes of 8–15% that are still manageable for farm development—which often borders the optimal mid-altitude temperature zone. This overlap between manageable slopes and optimal climate in the mid-altitudes is a key spatial finding for strategic livestock planning. This complex topographical landscape presents both challenges and opportunities for livestock land development. High-slope areas require specialized management strategies to mitigate erosion risks while simultaneously maximizing sustainable land use potential for livestock farming.

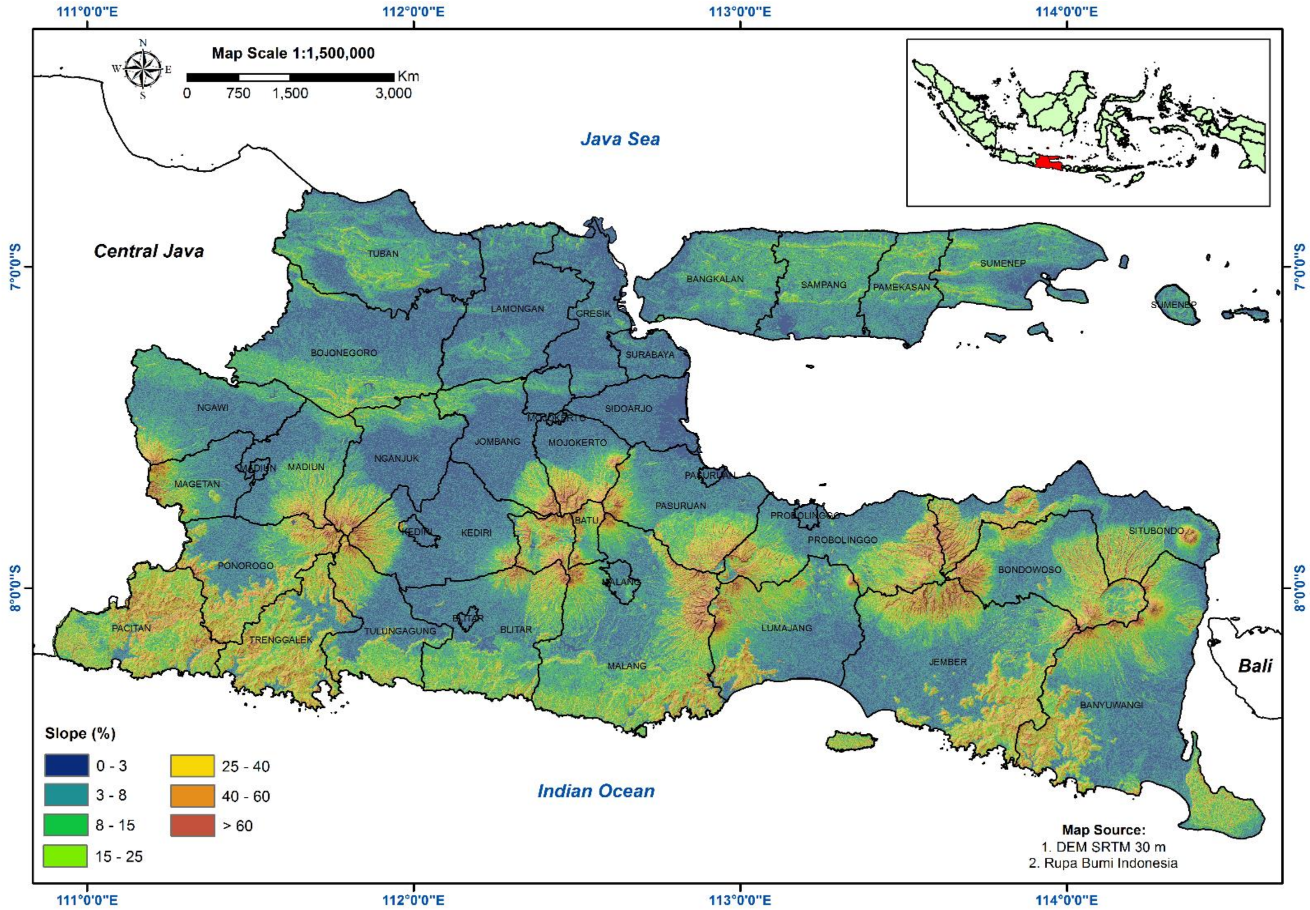

Figure 4. Spatial distribution of land slope in the study area

3.4 Correlation between land slope, temperature, and oxygen levels

The findings of this study indicate a significant relationship between elevation, temperature, and oxygen levels. As expected from established physical principles, statistical analysis confirmed that elevation has a strong inverse relationship with temperature ($p < 0.01$) and oxygen levels ($p < 0.05$). This aligns with the fundamental atmospheric laws where temperature decreases approximately 0.6°C per 100-meter elevation gain (Braak's formula), and oxygen availability reduces with decreasing atmospheric pressure at higher altitudes (Peacock's equation). The consistent patterns demonstrate that higher elevations are associated with lower temperatures and reduced atmospheric oxygen availability.

Land slope is often directly linked to elevation, which influences temperature and oxygen conditions. Lees et al. [8] emphasized that higher elevations generally exhibit lower temperatures due to decreasing atmospheric pressure and increased heat loss via radiation. This principle aligns with Braak's equation [10], which states that every 100-meter elevation increase results in a temperature decrease of approximately 0.6°C.

Furthermore, oxygen levels also decline with increasing elevation and land slope. Peacock [11] explained that lower air pressure at higher altitudes reduces oxygen molecule density per unit volume, which may induce hypoxia in livestock, particularly poultry, which are more sensitive to low oxygen levels. This phenomenon was also confirmed by Huang et al. [18], who found that chickens raised in low-oxygen environments experienced slower growth rates and increased metabolic stress.

High-slope areas also influence microclimatic conditions. Gonga-Saholiariliva et al. [19] demonstrated that steeper topographies tend to experience more extreme temperature variations due to differences in solar radiation exposure and surface drainage patterns. As a result, higher-slope regions often have more rapid temperature fluctuations compared to flatter areas.

3.5 Land suitability for dairy cattle

The land suitability analysis for dairy farming in East Java Province shows that areas with optimal temperatures (18–24℃) cover 972,739.17 hectares, making them ideal for maintaining cattle health and productivity (Table 3). These areas are primarily located in mid-elevation zones, such as mountain slopes and certain highland regions, which exhibit cool and stable climates (Figure 5). Cross-referencing Figure 5 with the temperature map (Figure 2) and slope map (Figure 4) reveals that this optimal zone forms a near-contiguous ring around the mid-slopes of East Java's major volcanoes. This pattern is not random but is a direct result of the region's volcanic geomorphology. The consistent elevation of these slopes creates a stable, cool microclimate, while the volcanic soils, though not directly studied here, are often fertile, supporting the forage production essential for dairy operations. The contiguity of this zone is significant as it suggests the potential for developing a connected dairy farming belt, which could facilitate logistics, milk collection, and extension services. West [20] reported that the optimal temperature range for dairy cattle is between 5℃ and 25℃, where temperatures above 25℃ may induce heat stress, negatively affecting feed intake, milk production, and reproductive efficiency.

In contrast, high-temperature areas (> 24℃) dominate lowland and coastal regions, covering 3,372,731.46 hectares, which are less suitable for dairy cattle farming due to the risk of heat stress. However, these lowland areas are also the primary locations of human population centers and infrastructure. This spatial mismatch between optimal dairy zones and existing economic hubs implies that developing the dairy belt in the mid-altitudes would require concurrent investment in rural infrastructure, such as cooling chains and access roads, to connect production areas with markets. Lees et al. [8] emphasized that high temperatures increase the likelihood of disease, disrupt livestock metabolism, and impair milk production efficiency. Heat stress in dairy cattle not only reduces feed efficiency but also affects reproductive performance, leading to longer calving intervals and decreased conception rates [20].

Table 3. Distribution of land suitability classes for dairy cattle

Temperature (℃)	Category	Description	Area (ha)
< 18	Low	Not ideal	177,663.42
18–24	Optimal	Ideal	972,739.17
> 24	High	Not ideal	3,372,731.46

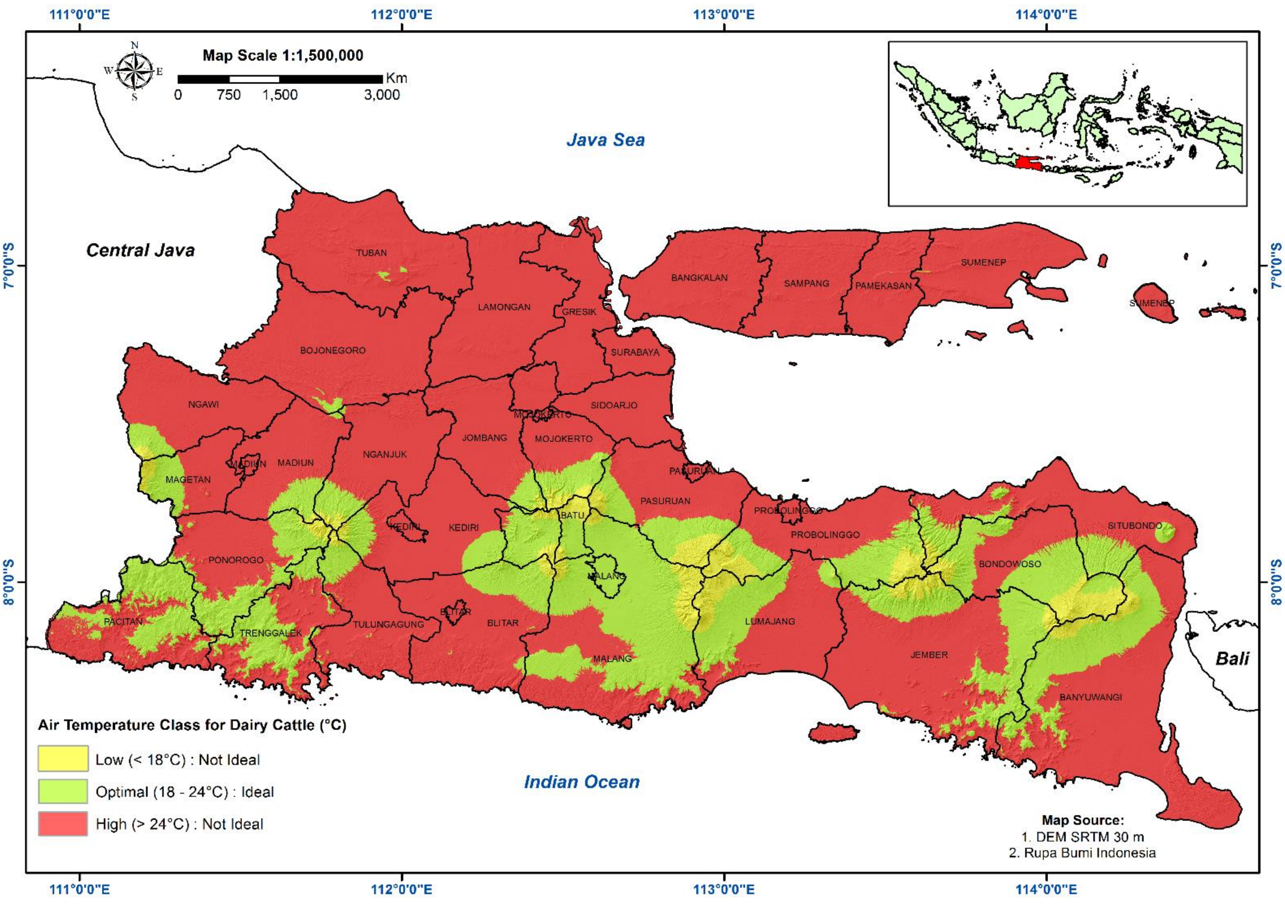

Figure 5. Land suitability for dairy cattle based on temperature variables

Similarly, low-temperature areas (< 18°C) are also considered unsuitable for dairy farming, as these regions only cover 177,663.42 hectares and are mainly found in high-altitude mountainous zones. Extremely low temperatures may induce cold stress, impacting metabolic efficiency and overall cattle health, particularly when combined with strong winds and high humidity [20]. Therefore, selecting locations with optimal temperatures is a critical factor in land-use planning for dairy cattle farming in East Java Province. This information provides an essential guideline for zoning and sustainable dairy farm management, ensuring efficient and productive livestock operations.

3.6 Land suitability for beef cattle

The land suitability analysis for beef cattle farming in East Java Province indicates that areas with optimal temperatures (20–26°C) cover a total of 3,143,572.2 hectares (Table 4), making them the most suitable zones for supporting beef cattle growth and productivity. These regions are primarily located in mid-elevation areas and certain mountain slopes, characterized by relatively cool and stable climates (Figure 6). The spatial pattern for beef cattle (Figure 6) shows a much larger suitable area compared to dairy cattle, encompassing not only the mid-altitude volcanic slopes but also extending into lower highlands and cooler parts of the uplands. This broader suitability is due to beef cattle's wider thermal comfort zone. The resulting suitable area forms a vast, interconnected region in the central and eastern parts of the province. This contiguity is advantageous for establishing large-scale beef cattle corridors. The analysis shows that a significant portion of this optimal beef zone overlaps with the manageable slope classes (0–15%), particularly in the rolling hills of the Malang Plateau and the eastern salient of Java. This reduces the potential conflict with steep slopes that constrain dairy farm development in some areas. Gaughan and Cawdell-Smith [21] emphasized that maintaining optimal environmental temperatures is crucial for ensuring beef cattle welfare and production efficiency. Excessive heat or cold stress can negatively impact feed efficiency, growth performance, and overall cattle health.

High-temperature areas (> 26°C), covering 1,201,898.43 hectares, are predominantly found in lowland and coastal regions, such as Lamongan and Probolinggo Regencies. These areas are less suitable for beef cattle farming due to heat stress risks, which can reduce feed efficiency and meat production performance. Heat stress in beef cattle leads to reduced feed intake, slower growth rates, lower feed conversion efficiency, and increased susceptibility to diseases [21].

Conversely, low-temperature areas (< 20°C), covering only 177,633.42 hectares, are primarily located in high-altitude mountainous regions, such as Mount Arjuno and Mount Semeru. Cold stress in beef cattle can increase energy requirements for thermoregulation, which in turn reduces feed efficiency and slows growth rates [21]. These findings provide a critical basis for decision-making in land management and allocation to enhance efficiency and sustainability in beef cattle farming in East Java. Understanding the relationship between environmental temperature and beef cattle performance is essential for optimizing livestock welfare and production efficiency.

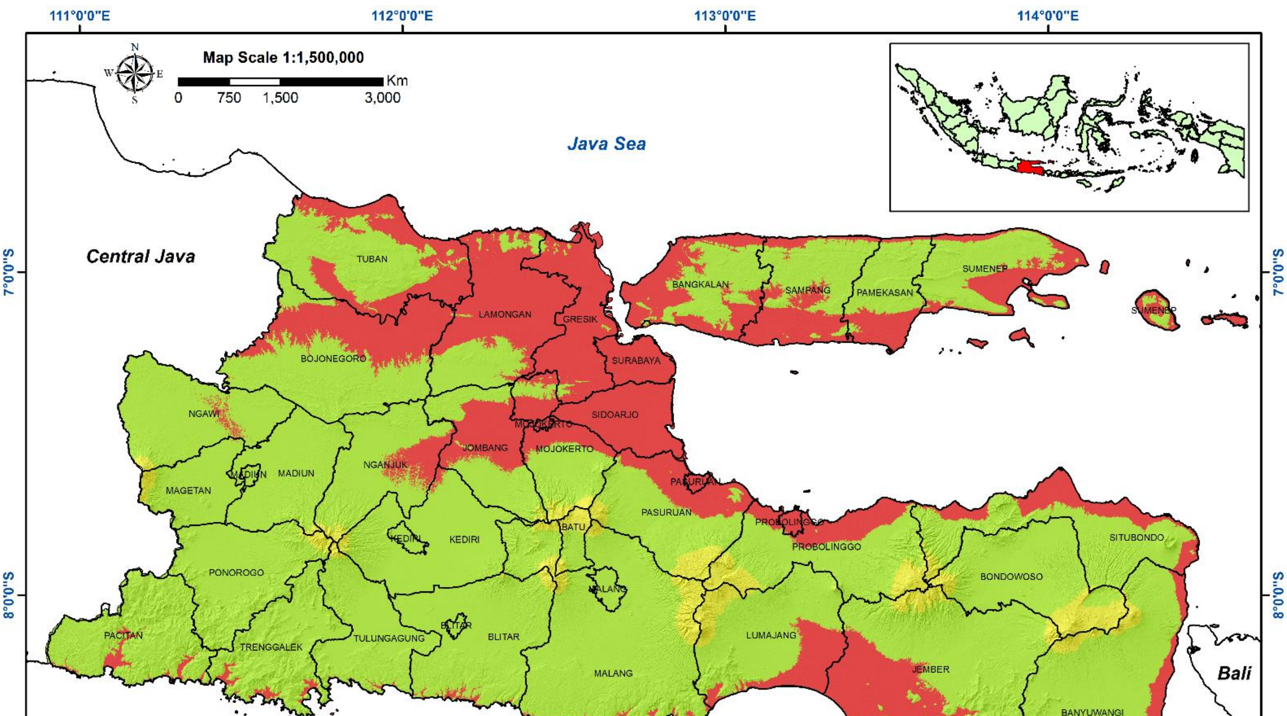

Figure 6. Land suitability for beef cattle based on temperature variables

Table 4. Distribution of land suitability classes for beef cattle

Temperature (℃)	Category	Description	Area (ha)
< 20	Low	Not ideal	177,633.42
20–26	Optimal	Ideal	3,143,572.2
> 26	High	Not ideal	1,201,898.43

3.7 Land suitability for chicken and quail

The land suitability analysis based on oxygen concentration for chicken and quail farming in East Java Province indicates that areas with moderate oxygen levels (18–19.62%) cover the largest area, totaling 4,239,018.99 hectares (Table 5). These areas are considered sufficient to support poultry respiration, particularly for chickens and quails, which require high oxygen availability to maintain health and productivity. The primary spatial finding for poultry is the near-universal suitability of the province from an oxygen perspective. The vast "Moderate/Suitable" class forms a contiguous blanket over all lowland and mid-altitude areas. The only clear exclusion zones are the fragmented, high-altitude peaks. This suggests that oxygen availability is not a major limiting factor for poultry farm location selection across most of East Java. Consequently, location decisions for poultry farms can be prioritized based on other factors, such as proximity to feed mills, processing plants, and major consumer markets in urban centers like Surabaya, Malang, and Kediri, rather than being constrained by atmospheric oxygen. This finding decouples poultry planning from the topographical constraints that significantly influence cattle farming. Heat stress in poultry can trigger various diseases and negatively affect both growth and egg production [22, 23]. Although their study primarily focused on heat stress, the importance of an optimal environmental condition, including adequate oxygen levels, is crucial for poultry health [24]. Areas with low oxygen levels (15–17.9%), which are less suitable, cover 2,821,122.91 hectares and are generally located in mid-elevation zones and mountain slopes. Meanwhile, areas with very low oxygen levels (< 15%), which experience severe hypoxia, account for only 1,992.15 hectares. These regions are found in high-altitude mountain ranges such as Mount Semeru and Mount Ijen, which are unsuitable for poultry farming due to insufficient oxygen availability, leading to metabolic and respiratory disorders in chickens and quails (Figure 7).

Table 5. Distribution of land suitability classes for chicken and quail

Oxygen (%)	Category	Description	Area (ha)
< 15	Very Low	Severe Hypoxia	1,992.15
15–17.9	Low	Not ideal	2,821,122.91
18–19.62	Moderate	Suitable	4,239,018.99

Toxic gases such as ammonia (NH_3), produced from poultry manure, can degrade air quality and negatively impact poultry health [25, 26]. Although this study primarily focused on toxic gas accumulation, it reinforces the significance of air quality, including oxygen availability, in poultry farming management. This study has several limitations, particularly in considering only oxygen concentration as the determinant of land suitability for poultry farming. However, other environmental factors such as temperature, humidity, and feed quality also play a vital role in poultry health and productivity. Additionally, the availability of high-resolution spatial data on oxygen levels across various elevations may be limited, potentially affecting the accuracy of land suitability mapping.

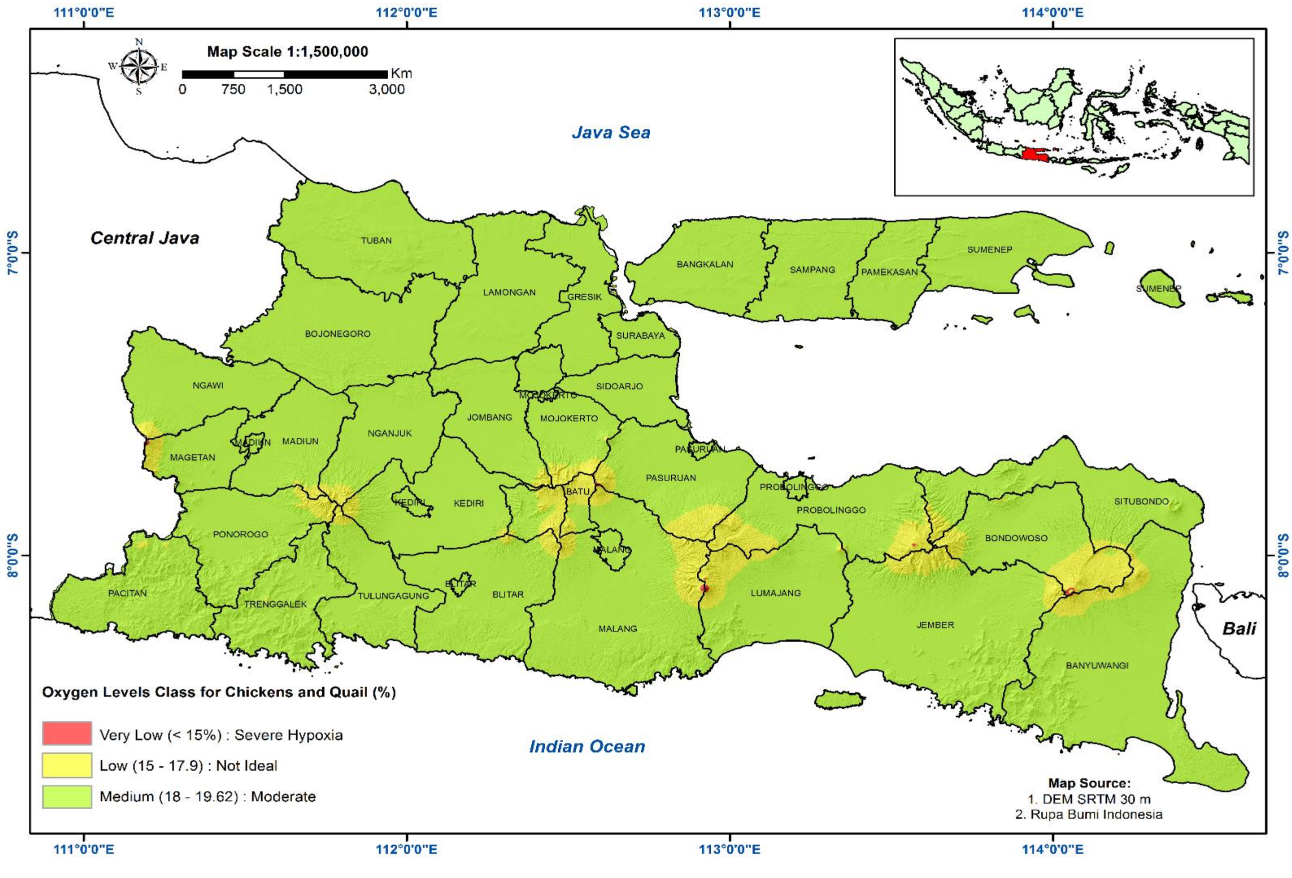

Figure 7. Land suitability for chicken and quail based on oxygen concentration variables

Despite these limitations, the study provides practical implications for policymakers and farmers in poultry farm management. Information on oxygen distribution can assist in optimal poultry farm zoning, helping to avoid areas with low oxygen levels that may reduce poultry productivity. Farmers can utilize this data to select farm locations with sufficient oxygen levels, thereby enhancing poultry health and production efficiency. Furthermore, in low-oxygen areas with other agricultural potential, implementing ventilation technology or enclosed poultry housing systems can be considered to improve air quality for poultry farming.

4. DISCUSSION

4.1 The impact of temperature on dairy and beef cattle productivity

Environmental temperature plays a fundamental role in the thermoregulation and productivity of both dairy and beef cattle. Dairy cattle, being high-metabolism animals, are particularly sensitive to temperature variations. The core finding of this study, as visualized in Figures 5 and 6, is the identification of a distinct, contiguous optimal temperature zone located consistently in the mid-altitude regions of East Java's volcanic slopes. This is not a random distribution but a direct mechanistic outcome of the region's unique geomorphology. The gradual decrease in temperature with elevation, as described by Braak's formula and confirmed by our strong correlation ($R^2 = 0.81$), creates a Goldilocks zone—a narrow altitudinal band where temperatures are consistently within the 18–26℃ range. This zone emerges because the lowlands experience heat accumulation, while the highlands suffer from excessive cold; the mid-slopes provide the perfect equilibrium. The contiguity of this zone, forming a ring around volcanoes like Semeru and Arjuno, is a result of the consistent elevation provided by their ancient lava flows and caldera structures, which create a stable, cool microclimate ideal for cattle. High ambient temperatures outside this zone, predominantly in the lowlands, induce heat stress, which negatively affects feed intake, nutrient metabolism, and ultimately, milk synthesis in dairy cattle and weight gain in beef cattle.

The physiological mechanism underlying this spatial pattern is the animal's effort to maintain homeothermy. In the lowland heat, cattle increase evaporative cooling through panting and sweating, processes that demand significant energy and divert metabolic resources away from production. This is compounded by reduced feed intake, a behavioral adaptation to decrease metabolic heat production. Conversely, in the highland cold, the animal must increase metabolic heat production to maintain core body temperature, again diverting energy from growth and milk production. Therefore, the spatial pattern we map is a direct visualization of metabolic efficiency. The contiguous mid-altitude band represents the geographic area where cattle can channel the maximum proportion of their dietary energy into production rather than thermoregulation. Studies have consistently shown that dairy cows raised in such lower-temperature environments produce higher milk yields compared to those kept in warmer regions. Furthermore, heat stress can also impair reproductive efficiency by altering hormone profiles, increasing calving intervals, and reducing conception rates.

Effective environmental management strategies, such as providing shade, cooling systems, and modified housing, are crucial to mitigating the negative effects of high temperatures on livestock productivity. For instance, using fans and misting systems can help cool down cattle and reduce heat stress-related impacts. However, our spatial analysis suggests that the most fundamental and cost-effective strategy is strategic site selection. Investing in a farm within the identified optimal zone pre-emptively reduces the need for and cost of intensive cooling infrastructure required in the lowlands.

While research on the impact of temperature on cattle productivity often focuses on temperature and humidity variables, our study demonstrates the critical importance of a third dimension: topography. It is the topography that dictates the spatial distribution of the microclimates to which the cattle are exposed. Other factors, such as feed management, genetic traits (e.g., incorporating slick-hair genes for heat tolerance), and overall health conditions, also play significant roles and should be integrated with spatial planning.

Policymakers and farmers can use this geospatial information to enhance cattle welfare and productivity at a regional scale. The clear, contiguous nature of the optimal zone provides a strong scientific basis for establishing "dairy and beef development corridors" in East Java. Implementing environmental management strategies, such as shade structures, proper ventilation, and cooling systems, remains important. However, the primary recommendation from this study is to prioritize the selection of new farm locations within the identified optimal mid-altitude zones. Optimizing feed formulations for specific climatic zones, such as incorporating protected fats in hotter areas, can also support milk production and cattle health, but this should be seen as a secondary measure to the primary strategy of optimal location.

4.2 The impact of oxygen concentration on chicken and quail productivity

Oxygen concentration is a critical factor in poultry farming, directly affecting metabolic efficiency, growth rates, and overall productivity in chickens and quails. In high-altitude areas with lower oxygen levels, poultry may experience hypoxia [18], a condition that fundamentally limits oxidative phosphorylation and ATP production at the cellular level. This often leads to reduced feed intake, slower weight gain, and lower egg production. Hypoxia disrupts cellular respiration and energy metabolism, forcing poultry to expend more energy to maintain basic physiological functions rather than focusing on growth and reproduction [27].

Our spatial analysis, presented in Figure 3 and summarized in Figure 7, reveals a critical and practical insight: the hypoxic areas unsuitable for poultry are highly localized and fragmented, confined to the peaks of the highest volcanoes. The vast majority of East Java's land area, including its densely populated lowlands and agriculturally productive mid-altitudes, falls within the 'Moderate' oxygen class (18–19.62%), which is sufficient for poultry respiration. This finding has a significant mechanistic implication: it decouples oxygen availability as a primary limiting factor for poultry farm siting across most of the province. The spatial constraint for poultry, unlike for cattle, is not a broad, contiguous zone of exclusion but rather pinpoint locations at extreme elevations.

Therefore, the mechanistic explanation for poultry productivity in East Java shifts from a direct oxygen limitation across the landscape to a more localized issue. For over 95%

of the province, the discussion must focus on other oxygen-related management aspects, primarily air quality within the poultry house itself. The buildup of toxic gases such as ammonia (NH_3) and carbon dioxide (CO_2) becomes a far greater daily threat to bird health and performance than ambient atmospheric oxygen [25, 26]. This means that ventilation system design and manure management are the primary operational levers for ensuring optimal respiratory health, not altitudinal location. Studies have shown that when oxygen levels decline, poultry performance is significantly affected, leading to higher mortality rates and an increased risk of respiratory diseases [28]. Conversely, maintaining optimal oxygen levels strengthens the immune system and improves overall production efficiency [29]. Selecting appropriate farm locations and ensuring adequate oxygen supply are essential to maintaining high poultry productivity and minimizing losses. These findings highlight the importance of incorporating oxygen concentration data into spatial land suitability assessments to optimize poultry farming across different topographical regions.

4.3 The impact of land slope on livestock farming operational cost

Land slope plays a critical role in determining the operational efficiency and economic viability of livestock farming, influencing everything from infrastructure development and feed distribution to animal transportation and manure management. The spatial slope analysis presented in Figure 4 reveals a province divided between largely flat northern lowlands and intensely steep southern and central highlands. The mechanistic link between slope and cost is rooted in fundamental physics and engineering: steeper slopes exponentially increase the force and energy required for transportation, complicate the construction of stable foundations for buildings, and accelerate soil erosion, which damages infrastructure and degrades pastureland. Steeper slopes pose greater technical challenges, requiring specialized technology and equipment, which can significantly increase operational costs. Stokes et al. [30] found that on land with slopes greater than 15%, the use of agricultural machinery becomes inefficient and presents higher risks of operational accidents. Additionally, these conditions lead to higher labor demands and greater investments in erosion control infrastructure, feed distribution pathways, and water supply systems.

A key finding from integrating our slope map with our temperature suitability maps is the identification of a 'cost-climate trade-off'. The optimal temperature zone for cattle in the mid-altitudes frequently coincides with the 15–40% slope class. This creates a direct trade-off: farmers can choose the flat northern lowlands for lower construction costs but face high heat stress mitigation costs, or they can choose the optimal climate in the mid-slopes but face higher initial capital costs for terracing, specialized building designs, and reinforced access roads. The contiguity of the optimal temperature zone, however, offers a potential solution. By planning development along this contiguous band, the costs of shared infrastructure like roads and processing facilities can be amortized over a larger area, thereby reducing the individual burden on each farm. Livestock farms located in lowland areas tend to have higher efficiency in material transportation and overall accessibility [31, 32]. Meanwhile, erosion caused by heavy rainfall in steep-slope areas can lead to land degradation, reducing the productive capacity of livestock farms. Garrity [33] noted that agricultural investments in highland areas with steep slopes increase production costs compared to flat areas.

This analysis moves beyond simply stating that slopes are costly. It provides a spatially explicit framework for evaluating the economic trade-offs. For policymakers, this means that incentives for livestock development in the optimal highland zones must be coupled with investments in rural infrastructure to lower the barrier to entry. For farmers, it provides a clear calculus: the higher initial investment in slope-friendly infrastructure can be justified by the long-term savings in feed efficiency, animal health, and production output gained from the superior climate.

Policymakers and farmers can utilize this information for better land planning and management. For instance, steep-slope areas should be designated for activities requiring minimal mechanical intervention or should be planted with erosion-control vegetation. Investing in appropriate technology and infrastructure, such as specialized farming tools for steep land and erosion control systems, can improve operational efficiency. Additionally, training workers on proper operational techniques in sloped areas can reduce accident risks and enhance productivity.

4.4 The role of spatial data in livestock land mapping

The use of spatial data in livestock land mapping is becoming increasingly important to optimize land-use efficiency and promote sustainable livestock production. Geographic Information Systems (GIS) and remote sensing technologies provide valuable insights into key environmental factors such as elevation, slope, temperature, and oxygen levels, all of which play a crucial role in determining livestock land suitability. The core methodological contribution of this study is the demonstration of how freely available DEM data can be transformed, through physiological models (Braak, Peacock) and GIS analysis, into actionable, species-specific suitability maps. This process bridges the gap between animal environmental physiology and practical land-use planning. Gonga-Saholiariliva et al. [19] highlighted that Digital Elevation Models (DEM) allow precise topographical analysis, which can be used to identify the most favorable areas for various livestock species. Moreover, integrating DEM with climate datasets enhances the accuracy of land suitability assessments by accounting for temperature fluctuations and oxygen availability, both of which are critical for livestock health and productivity [8, 18].

This study specifically advances the field by moving beyond single-factor analysis to a multi-parameter classification scheme that reflects real-world decision-making. The most powerful insights emerged not from viewing each parameter in isolation, but from observing their spatial interplay—such as the overlap of the optimal temperature band with manageable slopes, or the near-universal suitability of the province for poultry from an oxygen perspective. This integrated spatial view allows for a more nuanced discussion and more robust recommendations than would be possible from statistical analysis alone. Spatial data analysis also enables the development of predictive models that assess land suitability based on various environmental variables, leading to more accurate decision-making in livestock farm planning. Malczewski [34] emphasized that integrating spatial data with machine learning algorithms can generate high-resolution maps categorizing land suitability, ensuring livestock are placed in environments that best match their physiological needs. Advances in spatial data utilization not only enhance livestock productivity but also support sustainable land management practices by minimizing environmental impact and optimizing resource use by preventing the establishment of farms in inherently unsuitable locations.

Despite its advantages, the use of spatial data in land mapping has certain limitations, which our study also encountered. The resolution of the DEM (30 m SRTM), while excellent for regional planning, may miss critical micro-topographical features relevant to a single farmstead. Furthermore, our models are based on steady-state assumptions (e.g., average temperature) and do not capture extreme weather events or seasonal variations that can significantly impact livestock. The most significant limitation is the exclusion of other vital factors due to data availability, such as soil fertility for forage production, water availability, land tenure, and proximity to markets. This underscores that our maps are a foundational screening tool, not a final site-selection determinant. Data availability constraints, data quality issues, and challenges in interpreting spatial datasets can impact the accuracy of land suitability analysis and modelling. Additionally, collecting and processing spatial data efficiently and developing more advanced spatial analysis methods and technologies are necessary to ensure the successful implementation of these technologies in sustainable land-use planning.

The practical implications of spatial data utilization in livestock farm planning are significant for both policymakers and farmers. For provincial policymakers, the generated maps provide a scientific basis for formal zoning regulations, preventing land-use conflict and guiding infrastructure investment towards the identified development corridors. For district-level planners and individual farmers, these maps serve as a powerful preliminary site-selection tool, dramatically narrowing the field of potential locations for detailed feasibility studies. With accurate land suitability information, policymakers can develop strategies to support livestock farming in optimal locations, improving production efficiency and animal welfare. For farmers, spatial data utilization facilitates better decision-making in farm site selection, feed management, and environmental risk mitigation, ultimately enhancing livestock productivity and farm sustainability.

5. CONCLUSIONS

This study underscores the critical importance of spatial analysis for mapping livestock land suitability in East Java Province, Indonesia, based on the key environmental parameters of temperature, oxygen concentration, and land slope. The findings reveal that optimal temperatures for dairy cattle (18–24℃) cover 972,739.17 hectares, while areas suitable for beef cattle (20–26℃) span 3,143,572.2 hectares. For poultry, zones with adequate oxygen levels (18–19.62%) are widespread, covering 4,239,018.99 hectares, whereas land with slopes exceeding 40% is deemed unsuitable for large-scale farming due to prohibitive operational challenges and erosion risks. These results provide a scientific foundation for optimizing livestock zoning to enhance production efficiency and promote sustainable land management.

Based on the distinct spatial patterns identified, specific and actionable policy recommendations are proposed. Firstly, the provincial government should designate the mid-altitude zones on the slopes of Mount Semeru, Arjuno-Welirang, and Wilis as Priority Livestock Development Zones for cattle, supported by incentives for critical infrastructure like access roads and cold chains. Secondly, for high-temperature lowland areas such as Tuban and Lamongan, policy should focus on promoting heat-resistant breeds and subsidizing heat stress mitigation technologies like evaporative cooling systems and shade structures. Thirdly, in ecologically sensitive steep-slope areas (> 40%) in the southern regions and mountain peaks, strict ecological protection measures must be enforced to restrict large-scale livestock farming and encourage conservation vegetation. Integrating these suitability maps into provincial and regional spatial plans (RTRW) is essential to guide sustainable investment and prevent land-use conflict.

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