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A systematic review on criteria for land suitability assessment for tea cultivation

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Tea (*Camellia sinensis* [L.] O. Kuntze) is one of the world's most widely consumed beverages and a vital cash crop supporting livelihoods, rural economies, and export revenues across the world notably Asia and Africa. It is a critical driver for socio-economic development and improvement of rural livelihoods, directly supporting Sustainable Development Goals (SDGs) related to poverty reduction and employment. Enhancing productivity in tea cultivation while ensuring efficient land utilization requires multi-criteria evaluation that integrates soil, climatic, topographic, accessibility, and socio-economic factors. Numerous studies have employed multi-criteria evaluation approaches in land suitability evaluation for tea cultivation, yet divergences in contextual settings, methodologies, data sources, criteria selection, weighting schemes, and suitability classifications have led to inconsistencies in accuracy, reliability, and comparability of results. This systematic review, conducted under the PRISMA framework, critically assesses these variations, harmonizes methodological approaches, and identifies best practices to provide a coherent baseline for future research and application. Findings reveal tea's high agro-ecological selectivity and most influential factors for tea suitability consistently identified in this study include soil properties, topography, climate, environmental surface and land cover indicators, and accessibility. Highly suitable conditions are defined by moderately acidic pH (4.5–5.5), well-drained, nutrient-rich loamy soils; 1000–2500 m above sea level elevation; 5–20° slope; annual rainfall of 1200–2500 mm; mean annual temperatures of 18–25 °C; relative humidity between 70–80%; areas dominated by forests or existing plantations with NDVI >0.6, and those located within 1 km of roads. Conditions beyond these thresholds fall into moderate or marginal suitability before being deemed unsuitable. Future research should prioritize comparative studies across diverse altitudinal gradients and climatic zones, using different tea varieties, to develop global suitability thresholds for promoting sustainability and resilience under climate change.

KEYWORDS

agro-ecological ratings, *Camellia sinensis*, land suitability evaluation, sustainability, tea suitability factors

1 Introduction

Tea (*Camellia sinensis* [L.] O. Kuntze) is among the key global cash crops with immense significance in world agriculture. It is reported as a leading cash crop in world agriculture (Hoang et al., 2021). It is a broad-leaved, perennial evergreen crop whose foliage structure and canopy characteristics show greater similarities to those of other woody vegetation types, including shrubs and orchards (Kang et al., 2023; Su et al., 2017). Its tender shoots, typically consisting of two leaves and a bud, are harvested and processed to manufacture the widely consumed tea beverage (Manzoor et al., 2024). Three tea principal varietal groups are recognized: *Camellia sinensis* var. *sinensis* (China type), adapted to cooler highland environments, *Camellia sinensis* var. *assamica* (Assam type), which thrives in warm and humid tropical conditions, and *Camellia assamica* sub spp *lasiocalyx* (Cambod or Southern type) (Mondal et al., 2004; Wambulwa et al., 2016). Numerous hybrids and locally adapted cultivars have been developed to enhance yield, stress tolerance, and quality traits. The *C. sinensis* var. *sinensis* is often associated with high-altitude agroecosystems and superior quality attributes, whereas *C. sinensis* var. *assamica* dominates lowland regions due to its vigorous growth and higher productivity (Ahmed et al., 2019). This genetic diversity underpins tea's ecological adaptability in different regions across the globe.

Tea holds a significant position globally, ranking as the second most consumed beverage after water, and is an integral part of the daily drink for nearly half of the world's population (Ahmed et al., 2010; Zhen, 2002). It ranks among the three most widely consumed beverages globally, alongside coffee and cocoa (Duncan et al., 2016; Li et al., 2011). From its origins in China, tea has spread across trade routes over centuries, becoming a key global cash crop and providing livelihoods for millions of people (Hajiboland, 2017), thereby contributing to rural incomes and food security in tea-producing countries. Global tea production is projected to expand steadily, with a compound annual growth rate of 5.7% from 2021 onward (Bermúdez et al., 2024). Bermúdez et al. (2024) further asserts that, this growth is largely driven by smallholder farmers, who accounted for approximately 60% of global tea output in 2022 and provided employment to more than 9 million of the 13 million people engaged in the tea sector worldwide. This makes it to be a critical driver for socio-economic development and improved rural livelihoods which aligns with the Sustainable Development Goals (SDGs) related to poverty reduction and employment.

Major producing countries including China as a leading producer followed by India, Sri Lanka, Japan, and Kenya each recording annual production exceeding 160,000 metric tons (Dutta et al., 2011; FAO, 2022; Galal, 2024; Kang et al., 2023; Mjanja et al., 2025). In Africa, Kenya remains the leading producer, contributing over 570,000 metric tons which is about 70% of the continent's total production followed by Malawi, Tanzania, and Uganda (Galal, 2024; Mjanja et al., 2025). Other tea notable producers include Turkey, Indonesia, Vietnam, Bangladesh, Argentina and Uganda (Dutta et al., 2011; FAO, 2022). Marked with expansions in tea-producing countries, over the last decade, the world tea per capita

consumption increased by 2.5 percent, with significant growth of tea production being observed in regions such as East Asia, Africa, Latin America, the Caribbean, and the Near East (FAO, 2022). This has been accelerated by the rising significance of tea in developing and emerging economies. Notably, a significant feature of global tea production is the dominant role of smallholder farmers, who grow approximately 60 percent of the total output (FAO, 2022), highlighting the importance of the tea sector in supporting employment generation in rural areas.

The international tea market holds an estimated value of USD 9.5 billion, serving as a vital source of export revenue for many producing nations. By 2030, global black tea production is expected to grow at an average annual rate of 2.1 percent, slightly below the 2.4 percent growth recorded in the previous decade (FAO, 2022). This trend is primarily driven by increased production in countries like China, Kenya, India, and Sri Lanka. Conversely, FAO (2022) projected that green tea output is projected to expand more rapidly at an annual rate of 6.3 percent largely due to anticipated production surges in China, where output is forecasted to nearly double by 2030. To meet projected targets for tea production, it is essential to undertake a rigorous assessment of land suitability criteria for tea cultivation. This process is vital for avoiding tea blind expansion by identifying and prioritizing areas with high tea agroecological potential for sustainable growth of tea sector across the world. Key determinants of tea growth such as climatic conditions, environmental parameters, and specific agronomic requirements of the crop must be thoroughly evaluated to inform strategic investment decisions in tea production. This is achieved through conducting land suitability evaluation, which serves as a basis for rational land resource planning and management for appropriate land use decision-making, thereby improving the efficiency of land use and the sustainable development of the environment (Staal et al., 2015). The land suitability evaluation is mainly performed by analysing natural and human factors, such as climate, soil conditions, topography, and vegetation indices, to assess the potential and limitations of land use (Das et al., 2020).

Predominantly cultivated in tropical and subtropical zones, tea is widely recognized as a representative example of an intensively managed cash crop system, particularly within subtropical regions. In terms of agro-ecological requirements, the tea crop is too selective, making a limited number of areas suitable for tea cultivation across the world. Because it needs a relatively warm temperature and moist climate, tea grows only in tropical and subtropical regions (Abdulle and Woyesa, 2023). Tea cultivation necessitates a consistent annual rainfall ranging between 1,200 mm and 2,200 mm, uniformly distributed throughout the year, and thrives best within an optimal temperature range of 13 °C to 30 °C (Chen et al., 2022; FAO, 2015; Gahlod et al., 2017; Hajiboland, 2017; Kariuki et al., 2022; Li et al., 2012). For optimal growth and development, the tea plant requires well-drained soils with a slightly acidic pH, ideally between 4.5 and 5.6 (FAO, 2015; Kariuki et al., 2022). In terms of soil texture, tea performs poorly on sandy soils but grows favourably in clay loam, loamy clay, and sandy clay loam soils (Dengiz et al., 2020; Hajiboland, 2017). Topographic attributes such as elevation, slope, and aspect significantly influence tea plant

development and its chemical composition by shaping the micro-climatic conditions that regulate soil moisture retention and drainage (Khormali et al., 2007). Optimal tea growth is typically achieved on gentle slopes ranging from 5° to 10° (equivalent to 13–25%) and at elevations between 1,500 and 2,250 meters above sea level (FAO, 2015; Hajiboland, 2017; Kariuki et al., 2022).

Identifying optimal areas for tea cultivation to enhance production has been the focus of numerous studies, many of which have employed diverse criteria to assess land suitability for tea cultivation. These criteria encompass a range of biophysical and environmental factors, including soil chemical properties such as soil reaction (pH), organic matter, nitrogen, phosphorus, potassium, and cation exchange capacity (Chen et al., 2022; Fayyaz et al., 2021; Saygin et al., 2023; Wu et al., 2013; Xing et al., 2022), as well as soil physical attributes like soil depth, texture, and drainage (Sahu et al., 2023). Topographic variables, particularly elevation, slope, and aspect, have also been commonly incorporated into suitability assessments for tea cultivation (Chen et al., 2022; Dolui, 2024; Jin et al., 2011; Li et al., 2012; Abdule and Woyesa, 2023; Pramanik, 2016; Wu et al., 2013; Xing et al., 2022). Additionally, environmental surface and land cover characteristics, including land use/land cover (LULC) classifications and vegetation indices such as normalized difference vegetation index (Sahu et al., 2023), climatic factors namely rainfall, temperature, and relative humidity (Mallick et al., 2024; Wu et al., 2013), accessibility factors such as proximity to roads and rivers (Das et al., 2020; Dolui, 2024; Mallick et al., 2024; Xing et al., 2022) have been widely acknowledged as among the critical determinants for suitable lands for tea cultivation.

While these studies collectively provide a broad overview of the multiple factors influencing land suitability for tea cultivation, the selection of criteria has often been shaped by contextual constraints, such as geographic location, data availability, and resource limitations. Consequently, many assessments offer fragmented insights, lacking a unified analytical framework that integrates these variables comprehensively. This fragmentation highlights a critical need for a systematic synthesis of current literature—one that can elucidate common patterns, assess the frequency and variability of applied criteria, and identify areas where current multi-criteria evaluation approaches can be improved. This systematic review seeks to address that gap by consolidating findings across relevant studies to develop a more holistic understanding of the key determinants of land suitability for tea cultivation. The review involves a detailed examination of methodologies, data sources, derived criteria, and the relative importance of various criteria used in tea suitability assessments. Furthermore, it identifies the most recurrently applied and influential criteria, offering a comparative perspective on how these criteria have been utilized across different agroecological contexts. By offering a comprehensive synthesis of current research, this review aims to support the development of more robust, data-informed approaches to land evaluation for tea cultivation. In doing so, it contributes to enhancing the accuracy and reliability of multi-criteria land suitability assessments and supports the strategic expansion of tea production to meet rising global demand. The findings presented herein are intended to guide both future research and practical decision-making in land use planning for sustainable and high-yielding tea cultivation.

1.1 Rationale of the review

In the field of agriculture, evaluation of land performance for a specific crop is a fundamental step toward ensuring the optimal use of available land resources for sustainable agricultural productivity (Perveen et al., 2008). Within the context of global tea production, one of the most pressing priorities is the improvement of agricultural land management practices and the implementation of suitable cropping patterns designed for tea cultivation, in order to enhance productivity while ensuring efficient land resource utilization. Achieving this goal necessitates the adoption of a robust multi-criteria land evaluation framework. A multi-criteria land evaluation approach integrates a range of factors to produce a comprehensive assessment of land suitability. Although a growing number of studies have employed multi-criteria analysis for evaluation of land suitability for tea cultivation, considerable divergence exists in the contextual settings, methodological frameworks, types of data employed, criteria selection, the weighting scheme of criteria, and classification of suitability levels within final outputs such as suitability maps and reports. These discrepancies contribute to inconsistencies in accuracy, reliability, and comparability of results across studies. This variability underscores the need for a systematic review to critically assess and synthesize current literature on land suitability for tea cultivation. The primary objective of this review is to consolidate the diverse methodological approaches, evaluate the most frequently employed criteria, and rank their significance based on their recurrence and impact in the literature. Furthermore, the review aims to identify prevailing knowledge gaps, examine the extent of methodological uncertainty and accuracy across studies, and offer recommendations for standardizing the parameters and evaluation metrics used in multi-criteria assessments. By systematically analysing the current body of research, this review contributes to the advancement of a unified framework for land suitability evaluation for tea cultivation. It serves not only to inform evidence-based decision-making in land use planning for tea cultivation but also to guide future research toward the development of more precise, consistent, and practical land assessment models.

2 Systematic review framework

2.1 Articles search

This systematic review was conducted in accordance with the updated Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, which offer comprehensive and revised recommendations for reporting systematic reviews. The current review's PRISMA process consisted of four phases: identification, screening, eligibility, and inclusion according to Page et al. (2021). The articles and reports were searched from reputable academic databases, including ScienceDirect, Google Scholar, EBSCOhost, MDPI, Web of Science Core Collection, PubMed, Scopus, AGRIS, and SpringerLink without restricting the search to a specific time period. In areas where published articles were limited, relevant published reports were also considered. In this

study, the choice of each search expression was based on the defined search keywords targeting the title, keywords, and abstract of relevant studies. The search keywords included: (“tea” OR “tea crop” OR “tea cultivation” OR “tea production”) AND (“suitability” OR “suitability analysis” OR “land suitability” OR “land suitability assessment” OR “land evaluation” OR “suitability evaluation”) AND (“criteria” OR “multi-criteria” OR “factors”) AND (“multi-criteria approach” OR “multi-criteria land evaluation” OR “multi-criteria analysis” OR “multi-criteria decision-making approach”) AND (“GIS” OR “Geographic Information System” OR “geospatial” OR “geoinformation” OR “machine learning”). The literature search was restricted to publications in the English language and multilingual texts that included English as one of the languages of publication. Theoretically, the search targeted articles and reports containing relevant information on criteria for assessing land suitability for tea cultivation, and global tea production information.

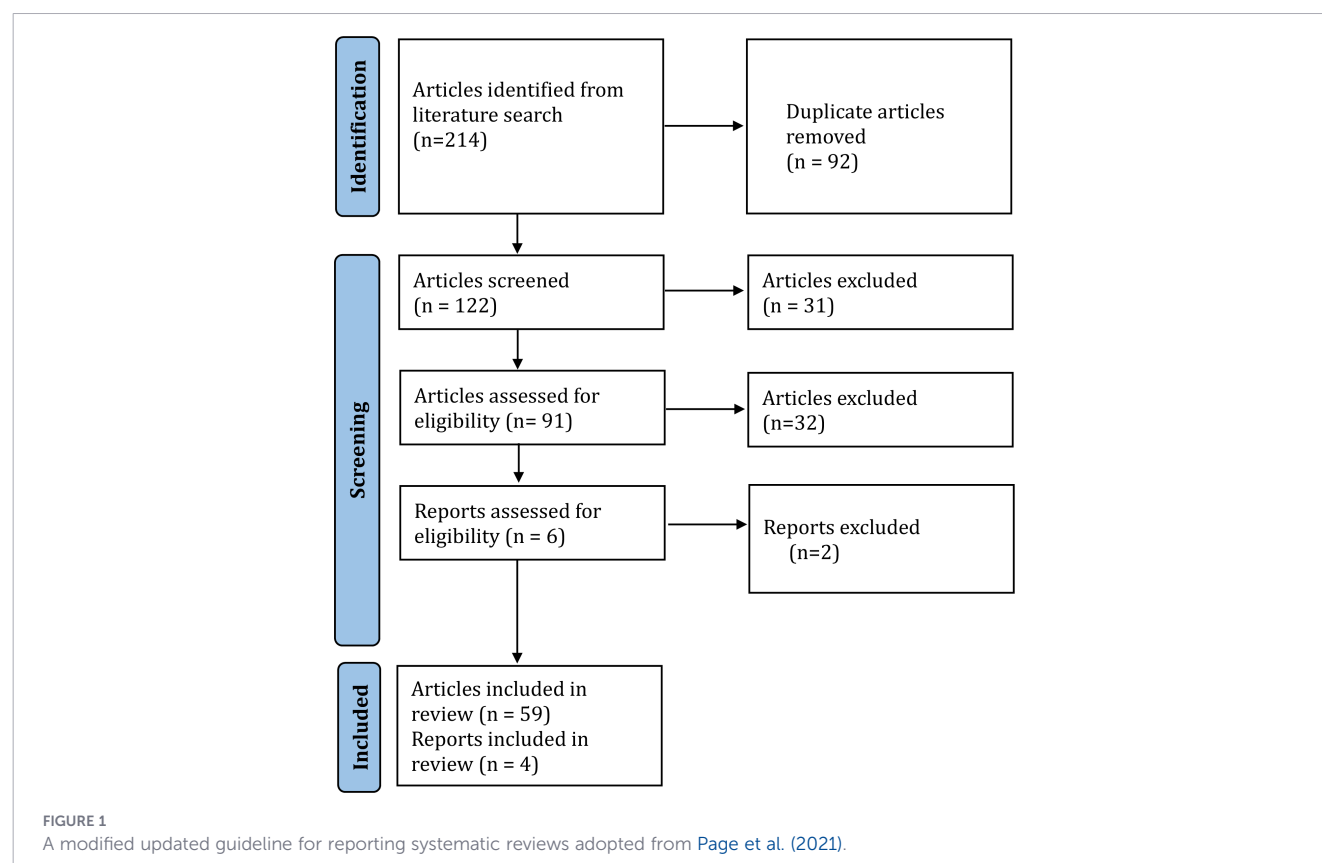
2.2 Articles screening

A total of 214 publications were initially identified through web search. After removing 92 duplicate records, 122 articles remained for further assessment, during which their titles were examined for alignment with the review’s focus. As a result, 31 papers were excluded for not meeting the necessary criteria. The remaining 91 articles then underwent a comprehensive evaluation of their titles, abstracts, and full texts to determine final eligibility based on predefined inclusion criteria. Studies were considered eligible for inclusion in the review process if they met one or more of the

following: (1) provided detailed information on global tea production; (2) assessed, identified, or mapped land suitability for tea cultivation; (3) employed multi-criteria analysis to delineate areas suitable for tea cultivation using one or more of factors that included soil, topographic, climatic, accessibility, or socio-economic variables; (4) explored environmental and agronomic conditions favourable for tea growth; and (5) were published exclusively in English or, in the case of multilingual texts, included English as one of the publication languages. Following detailed screening, 32 articles were excluded, leaving 59 studies that satisfied the inclusion criteria after full-text review. Additionally, 6 reports were assessed, of which 2 were excluded after thorough eligibility screening. Ultimately, 59 articles and 4 reports were selected for systematic review, providing the basis for examining and discussing the factors involved in multi-criteria land suitability assessment for tea cultivation. [Figure 1](#) presents the review process, tracing the progression from the initial database searching to the final selection of eligible studies.

2.3 Literature data sources

A robust and scientifically sound multi-criteria evaluation (MCE) for land suitability assessment in tea cultivation requires the integration of diverse and accurate datasets from field and laboratory analyses, as well as datasets sourced from various institutions and platforms. These data sources, play a pivotal role in enhancing the reliability of spatial and environmental modelling, thereby supporting informed and sustainable land-use decisions. Soil parameters are among the key factors in assessing land



suitability for tea cultivation. Key soil factors which have been identified in literature sources cited in the current review include soil pH, electrical conductivity (EC), soil organic matter (SOM), soil organic carbon (SOC), nitrogen (N), phosphorus (P), potassium (K), base saturation (BS), cation exchange capacity (CEC), calcium (Ca), magnesium (Mg), soil depth, texture, moisture, drainage, bulk density, soil type, and geology. Data for these factors were obtained through field surveys and laboratory analyses (Chen et al., 2022; Fernando et al., 2023; Gahlod et al., 2017; Xing et al., 2022), as well as from local agricultural research centres (Das et al., 2020), irrigation development authorities (Abdulle and Woyesa, 2023), and academic institutions (Rahaman and Aruchamy, 2022). In addition, a number of spatially explicit data were obtained from secondary sources such as digital soil maps (Gahlod et al., 2017; Li et al., 2012), the International Soil Reference and Information Centre (ISRIC) (Sahu et al., 2023), FAO GeoNetwork (Jayasinghe et al., 2019), and the European Soil Data Centre (ESDAC) (Dolui, 2024). National institutions such as the National Atlas & Thematic Mapping Organisation (NATMO) (Pramanik, 2016) and the National Earth System Science Data Centre (Chen et al., 2025) in India, provide comprehensive soil datasets. Satellite platforms, notably Landsat 8 OLI/TIRS (Dolui, 2024; Pramanik, 2016), were employed to derive soil-related indices and proxies notably soil moisture.

Literature data further demonstrated that topographic factors including elevation, slope, aspect, hillshade, and landform types were typically extracted from global elevation datasets such as the Shuttle Radar Topography Mission (SRTM) DEM (Sahu et al., 2023), ASTER DEM (Dolui, 2024; Rahaman and Aruchamy, 2022), and national topographic maps (Li et al., 2012). Other sources such as the Geospatial Data Cloud System of the Computer Network Information Centre of the Chinese Academy of Sciences (Chen et al., 2022, 2025; Xing et al., 2022) further supplemented the spatial resolution of terrain data used in tea suitability assessments. Key climatic factors which have been considered essential for determining the thermal and moisture regimes suitable for tea cultivation, include rainfall, temperature, relative humidity, and sunshine duration. Literature data indicated that, these parameters were sourced from a combination of local agricultural research institutions (Das et al., 2020), national meteorological departments and stations (Li et al., 2012; Mallick et al., 2024; Rahaman and Aruchamy, 2022), and international platforms such as the WorldClim database (Jayasinghe et al., 2019; Abdulle and Woyesa, 2023), China Meteorological Data Network (Chen et al., 2022), NASA POWER (Mallick et al., 2024), and the Climatic Research Unit of the University of East Anglia (Sahu et al., 2023). Remote sensing data from satellites such as Landsat 8 OLI/TIRS (Dolui, 2024) and national meteorological data centres (Chen et al., 2025) have been also utilized to enhance temporal and spatial coverage.

Environmental factors notably surface and land cover characteristics, including land use/land cover (LULC) classifications and vegetation indices such as the normalized difference vegetation index (NDVI), have been crucial for identifying tea suitable areas through examining spatial patterns of land utilization and vegetative vigour. Literature demonstrates that, these datasets have been retrieved from Sentinel-2 imagery via the Copernicus Open Access

Hub (Chen et al., 2022; Das et al., 2020), ESRI's global land cover products (Abdulle and Woyesa, 2023), Landsat 8 imagery (Sahu et al., 2023)), maps from local land resource departments (Li et al., 2012), and agricultural departments (Jayasinghe et al., 2019). Accessibility-related factors such as distances to roads, rivers, settlements, processing factories, and tea estates are also important and data for these factors were shown to be sourced from local agricultural institutions and national spatial statistics (Das et al., 2020), OpenStreetMap (OSM) (Dolui, 2024; Mallick et al., 2024; Pramanik, 2016), Google Earth, and geological survey websites (Dolui, 2024). Lastly, indicators of productivity and performance such as tea yield and production statistics that provide empirical benchmarks for validating model outputs and assessing land suitability outcomes were derived primarily from local statistical yearbooks (Chen et al., 2022).

Literature data showed that, the growing diversity and accessibility of data sources now make it possible to conduct reliable multi-criteria land suitability assessments for tea cultivation, even in the absence of extensive fieldwork or laboratory analyses, thereby largely preventing the blind expansion of tea plantations. Online platforms such as ISRIC, FAO GeoNetwork, WorldClim, Landsat, Sentinel, and other geospatial databases, when complemented by data from the field and laboratory analysis, and national meteorological and agricultural institutions for ground-truthing and regional specificity, can provide highly dependable results.

3 Results and discussion

3.1 Overview for geographical coverage of studies on multi-criteria land suitability for tea cultivation

The global literature on multi-criteria land suitability assessment for tea cultivation remains fragmented and uneven across continents, with studies largely concentrated in major tea-producing countries and regions. The review of existing studies in Figure 2 reveals that over 81% of the studies have been conducted in Asia, while the remaining 18.2% have been carried out in East Africa and the Middle East. Most research has been conducted in Asia,

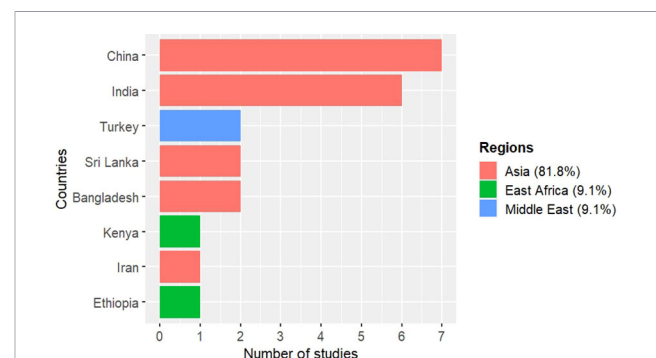


FIGURE 2
Geographical coverage of studies on multi-criteria land suitability for tea cultivation.

particularly in China's famous tea producing provinces such as Zhejiang, Anhui, Guizhou, Guangdong, and Hubei, and in India especially in the Darjeeling district of West Bengal, the Wayanad district of Kerala, the Nilgiri Biosphere Reserve of Tamil Nadu, and Assam region. Smaller but notable contributions come from Sri Lanka, particularly Nuwara Eliya district, Bangladesh in the Sylhet region, and Iran. In Africa, despite the prominence of Kenya to be among the global major tea-producers, scholarly contributions remain relatively limited, while Middle East is represented solely by studies in Turkey's Rize province. By contrast, Latin America and North America, where tea is grown in small pockets of countries like Argentina, Brazil, and the United States (notably Hawaii and South Carolina) and tea is not a strategic economic crop in these areas, are almost entirely absent from the literature. This absence reflects both the marginal scale of tea cultivation in these regions and the predominance of alternative cash crops such as coffee, cocoa, maize, and soybeans. Furthermore, large areas of these continents do not naturally conform to the topographical and climatic conditions required for extensive tea production, rendering tea suitability assessments a comparatively low research priority relative to crops of greater economic and agronomic significance.

Fragmentation of global literature on multi-criteria land suitability assessment for tea cultivation shows how research priorities are often dictated by local economic importance and historical pathways of crop diffusion. The scale of tea production in America is much lower compared to that in Asia and East Africa, which can be attributed to its later introduction to America and lower environmental suitability compared to other areas notably Asia or East Africa. This makes systematic land suitability assessments a low priority in America compared to Asia or East Africa. Consequently, the global literature on tea suitability remains dominated by regions where tea is a cornerstone of livelihoods, export earnings, and cultural identity. This imbalance calls for greater inclusivity in research coverage, both to capture emerging niche tea industries in the Latin America and to establish more globally standardized criteria for suitability assessment.

3.1.1 Assam tea landscape as a representative of high-suitability tea-producing regions

The Assam region of northeastern India, located along the Brahmaputra Valley, represents the largest contiguous tea-growing landscape globally and plays a central role in the global tea industry (Parida et al., 2024). The region is characterized by low-altitude to gently undulating terrain, high annual rainfall exceeding 2000 mm (Gogoi and Rao, 2022), and persistently warm and humid climatic conditions, which collectively favour rapid vegetative growth and high biomass production. According to Parida et al. (2024), tea cultivation in Assam is predominantly based on *Camellia sinensis* var. *assamica*, a variety well adapted to tropical environments and known for its high yield potential and distinctive strong, malty flavour profile.

The region contributes over 50% of India's total tea production, with annual outputs typically ranging between 630 and 700 million kilograms (Acharyya et al., 2025; Kandarpa et al., 2026; Leher, 2026; Roy et al., 2021), accounting for a substantial share of global tea

supply. According to Das et al. (2021) soils in the region are generally deep, fertile, and alluvial in origin, supporting intensive plantation systems, although sustained productivity often requires careful nutrient and water management. Despite these favourable conditions, the sector faces emerging challenges related to climate variability, including excessive rainfall, flooding, and temperature fluctuations (Sarma et al., 2022), which have begun to affect yield stability. This landscape exemplifies how optimal climatic and edaphic conditions, combined with suitable tea varieties, support large-scale production systems, while also highlighting the importance of adaptive management in sustaining productivity under changing environmental conditions.

3.2 Methods employed in determining the important influential factors affecting tea cultivation

3.2.1 Assigning weights using analytic hierarchy process

The Analytic Hierarchy Process (AHP), developed by Saaty in the 1970s, has emerged as the most applied systematic multi-criteria decision-making (MCDM) tool in tea agricultural land suitability assessments due to its precision, robustness, reliability, and capacity to incorporate both expert judgment and empirical evidence (Chen et al., 2022; Das et al., 2020; Dolui, 2024; Fayyaz et al., 2021; Jayasinghe et al., 2019; Li et al., 2012; Mallick et al., 2024; Abdulle and Woyesa, 2023; Pramanik, 2016). In tea land suitability studies, the AHP is utilized to structure the decision-making framework hierarchically and assign relative weights to a set of biophysical and environmental variables influencing tea cultivation suitability. These weights are derived through a combination of expert consultations with tea lead farmers, extension officers, agronomists and researchers, alongside a thorough review of relevant literature (Chen et al., 2022; Das et al., 2020; Rahaman and Aruchamy, 2022). The AHP methodology is undertaken through several standardized steps: establishing a pairwise comparison matrix to evaluate the relative importance of each criterion against other criteria, normalizing the matrix values to compute the final priority weight for each criterion, and finally testing the consistency of judgments to ensure logical coherence (Chen et al., 2022). The AHP pairwise matrix comparison employs Saaty's fundamental 1–9 scale (Table 1), where '1' denotes equal importance and '9' reflects the higher preference of one criterion over another (Beynon, 2002; Murmu et al., 2019; Njifen et al., 2024). This structured scoring mechanism allows for suitability analysis driven by objective quantification of expert preferences for factors influencing tea growth and productivity (Feizizadeh et al., 2014; Feizizadeh and Blaschke, 2013).

3.2.2 Weight assignment using the DEMATEL method in tea land suitability assessment

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique is a robust multi-criteria decision-making (MCDM) tool that has been employed in various studies to determine the relative importance and complex causal relationships

TABLE 1 The fundamental scale (Saaty, 2002).

Intensity of importance (absolute scale)	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment moderately favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	Used when compromise between two judgments is needed
Reciprocals		If activity i is assigned a value when compared to j, then j gets the reciprocal when compared with i
Rationals		Ratios arising from the scale; finer values such as 1.1, 1.2, etc., may also be used when needed

among different land suitability criteria for tea cultivation (Dolui, 2024; Jayasinghe et al., 2019; Mallick et al., 2024). In tea cultivation, this method offers a structured approach to unravel the complex interdependencies and inter-relationship that exist between biophysical and environmental factors, thereby facilitating more accurate and insightful decision-making. Mallick et al. (2024) asserts that unlike conventional weighting methods, DEMATEL not only quantifies the influence of each factor but also distinguishes between cause-and-effect criteria, enabling planners to identify the most influential variables affecting tea suitability outcomes. DEMATEL methodology is operationalized through a five-step procedure whose execution include: (1) identifying direct relationships among selected criteria, (2) normalizing those relationships, (3) constructing the total relation matrix, (4) establishing causal associations, and (5) calculating the degree of influence for each factor. Expert evaluations and relevant literature inform the construction of the direct-relation matrix using a scale ranging from 0 (no influence) to 4 (very strong influence), reflecting the perceived magnitude of interaction between variables (Mallick et al., 2024).

Following normalization, the total relation matrix (T) is derived using the formula $T = Y \cdot (I - Y)^{-1}$, where Y denotes the normalized matrix and I is the identity matrix. This matrix facilitates the evaluation of how each factor affects and is affected by others. The sum of each row (R_i) indicates the total influence a criterion exerts, while the column sum (C_i) represents how much it is influenced by other criteria. The combination of R_i and C_i values enables the identification of each factor's centrality and net influence, where a positive ($R_i - C_i$) indicates a causative factor and a negative value categorizes it as an effect variable. The system threshold (α), calculated from the mean of the total relation matrix, further distinguishes the cause-effect relationship among parameters. The DEMATEL causal diagram visually captures these interrelationships, showing a clear division between criteria with dominant influence (cause group) and those that are predominantly influenced (effect group). Final weight values (W_i) are computed by normalizing the R_i values for each criterion using $W_i = R_i / \sum R_i$, ensuring that the derived weights reflect both direct impact and systemic interdependence. This application of the DEMATEL method in tea land suitability assessment provides a scientifically

grounded and analytically rich framework for understanding how various environmental and agronomic factors interact (Jayasinghe et al., 2019). Its ability to capture both the magnitude and direction of influence among criteria makes it particularly valuable in tea precision agriculture and spatial decision support systems, where tea cultivation must be optimized across diverse and interrelated land characteristics.

3.2.3 Assigning weights using machine learning techniques

Recent advancements in land suitability assessment for tea cultivation have seen the integration of machine learning algorithms to enhance the precision of factor weighting. Xing et al. (2022) and Sahu et al. (2023) employed a machine learning modelling approach using techniques such as Logistic Regression (LR), Random Forest (RF), Gradient Boosting (GBDT), XGBoost, AdaBoost, Gaussian Naïve Bayes (GNB), and Multilayer Perceptron (MLP). These models not only improved the predictive accuracy of suitability mapping but also offered robust, data-driven means of quantifying the relative importance of diverse agro-environmental variables influencing tea growth suitability.

3.2.4 Use of the modified LESE model in multi-criteria land suitability assessment for tea cultivation

The Modified Land Ecological Suitability Evaluation (LESE) model offers a refined framework for assessing the ecological suitability of tea cultivation by integrating GIS-based spatial analysis with expert-informed, multi-criteria decision-making. Building upon the FAO's traditional land evaluation principles, the modified LESE approach enhances conventional evaluation accuracy by addressing the inherent uncertainties and classification ambiguities of earlier models. Li et al. (2012) conducted a comprehensive suitability evaluation for tea cultivation in China's Zhejiang Province using LESE. In this suitability evaluation, key biophysical factors covering climate, topography, and soil characteristics were quantified, normalized, and structured into a comprehensive

evaluation hierarchy. To reduce subjective bias in weight assignment, the AHP was employed, ensuring statistical consistency across expert-derived pairwise comparisons. Crucially, the model integrated Grey Relational Analysis (GRA) to better capture subtle distinctions among suitability classes by measuring the relational proximity of factor values to optimal reference conditions. Using a continuous (0–1) scale, the modified model improved resolution in class boundaries and strengthened the sensitivity of factor comparisons, overcoming the threshold rigidity found in earlier classification-based methods. The resulting ecological suitability index, calculated through weighted summation of grey coefficients, supported more detailed and data-driven classification of land areas into highly suitable, moderately suitable, and unsuitable zones. The capacity of LESE model in this suitability evaluation generally demonstrated that this approach could significantly contribute to precision tea agriculture by aligning spatial data science with agro-ecological expertise for sustainable land use planning.

3.3 Most frequently considered factors in multi-criteria land suitability assessment for tea cultivation across reviewed studies

The dominant soil, climatic, topographic, and environmental factors included in the multi-criteria analysis for tea cultivation suitability were selected based on their critical influence on tea plant growth, their potential to limit productivity within the specific geographical context and availability of data. Figure 3 above shows the most dominant factors considered in MCE for land suitability for tea cultivation and how frequent they have been used in multi-criteria analysis. Based on these results, tea cultivation is highly sensitive to its growing environment, and the selection of soil, climatic, topographic, and environmental factors in MCE reflects their profound influence on the crop performance.

Elevation and temperature, which appeared as the most frequently cited parameters, are foundational to determining the

suitability of an area for tea cultivation. Elevation shapes the microclimate of tea-growing regions by influencing temperature, rainfall, humidity, and soil formation processes. Higher elevations, free from waterlogging, tend to produce higher-quality tea due to slower shoot growth, enhanced accumulation of catechins, tannins, and improved aroma and flavour profiles, despite lower yields (Das et al., 2020; Fernando et al., 2023; Abdulle and Woyesa, 2023; Tang et al., 2015). Similarly, temperature directly regulates the physiological development of tea plants; optimal mean temperatures are essential for photosynthetic activity, bud formation, and leaf expansion. Chen et al. (2025) asserts that extremes in temperature, whether too low or too high, can cause physiological stress, resulting in reduced yields and poor-quality leaves.

Slope, ranking third in frequency, is a crucial topographic variable that affects runoff, erosion, and the physical stability of plantation land. Gentle slopes promote favourable drainage and minimize erosion, contributing to optimal nutrient and water retention necessary for robust plant growth (Sahu et al., 2023). Equally important is slope aspect, which governs solar radiation exposure and thereby impacts evapotranspiration, soil temperature, and biological activity. In the Northern Hemisphere, where the majority of tea production takes place, south-facing slopes often result in rapid growth due to higher sunlight exposure, while north-facing slopes, though cooler, are typically more fertile and support better organic matter accumulation (Chen et al., 2022; Sahu et al., 2023). These topographic factors are indispensable in maintaining favourable edaphic and microclimatic conditions that tea plants demand. Soil pH emerges as a vital determinant due to tea's narrow tolerance range; it thrives best in acidic soils with pH levels between 4.5 and 5.5 (Das et al., 2020). At such pH levels, essential nutrients such as nitrogen, phosphorus, and potassium are fairly bioavailable, directly impacting shoot development and leaf quality (Hajiboland, 2017; Mallick et al., 2024; Sahu et al., 2023). Soil texture and organic matter, both moderately ranked, further regulate nutrient holding capacity, aeration, and moisture dynamics. Tea plants perform best

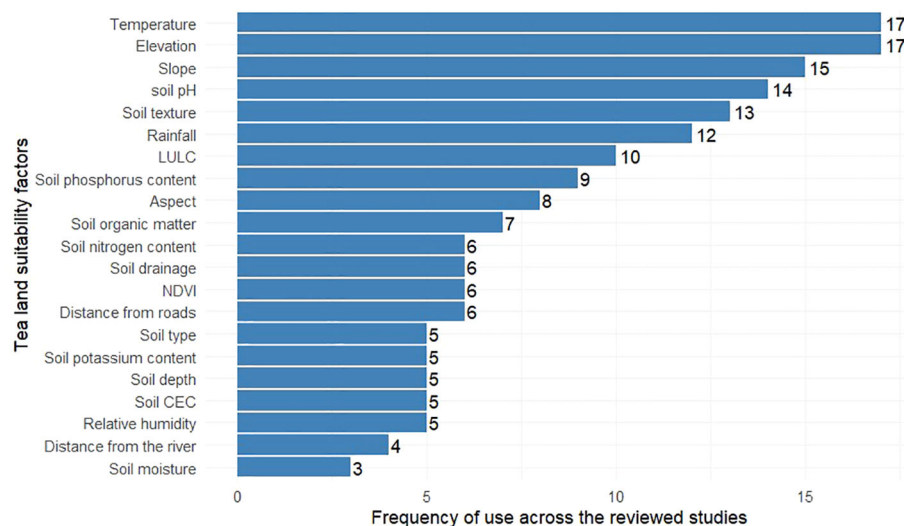


FIGURE 3

Most common factors used in multi-criteria land suitability analysis for tea cultivation across reviewed studies.

in loamy soils, which provide balanced aeration and water retention, unlike clay soils that often lead to compaction and poor drainage (Mallick et al., 2024). High levels of soil organic matter improve microbial activity and nutrient supply, thereby supporting vigorous vegetative growth and improved yields. Cation exchange capacity (CEC), another critical soil chemical parameter, enhances tea yield by improving nutrient retention and facilitating efficient uptake in the rhizosphere. This allows the plant to access essential ions over extended periods, even under fluctuating moisture conditions. Equally important is soil drainage, which ensures that roots receive adequate aeration and reduces the risks associated with waterlogging, which is detrimental to tea plants. Drainage not only supports healthy root development but also contributes to the prevention of surface runoff and erosion, protecting soil fertility and structure (Das et al., 2020).

Environmental and infrastructural parameters such as land use/land cover (LULC), NDVI, and proximity to roads and rivers also featured in the MCE. LULC patterns reveal spatial trends in land conversion and enable identification of areas viable for tea expansion. Forests, tea plantations, and farmland are favourable land use types, while urban and aquatic environments are generally unsuitable for tea cultivation (Chen et al., 2022; Das et al., 2020; Mallick et al., 2024; Abdule and Woyesa, 2023). NDVI serves as a reliable remote sensing indicator for assessing vegetation vigour, temporal growth trends, and the effectiveness of nutrient application practices (Mallick et al., 2024). Distance from roads is key to ensuring post-harvest efficiency, as shorter transport routes reduce spoilage and improve economic viability. Similarly, proximity to rivers supports irrigation and logistics, especially in remote or drought-prone areas (Das et al., 2020; Mallick et al., 2024; Xing et al., 2022).

Tea MCE studies underscore the multifaceted nature of tea cultivation suitability, where soil, topography, climate, and accessibility must be evaluated in an integrated framework. Each parameter contributes uniquely to shaping the biophysical environment in which tea cultivation thrive. Thus, successful tea plantation planning depends on a comprehensive understanding and balancing of these interacting factors to ensure sustainable, high-quality tea production.

3.4 Influential factors in tea land suitability based on AHP-derived relative importance weights

The most important influential factors were determined by calculating the weighted average of all Analytic Hierarchy Process (AHP)-assigned values for each important land suitability factor highlighted across the selected studies (Table 2). The AHP-derived weights highlight precipitation as the most influential factor in tea cultivation (18.98%), followed by elevation (14.73%) and slope (13.05%). This hierarchy reflects the critical role of climatic and topographic variables in shaping tea growth conditions, as rainfall ensures continuous moisture supply while elevation and slope regulate microclimate, soil erosion, and drainage. Temperature (12.24%) and soil moisture (11.80%) also emerge as significant determinants, consistent with their effects on physiological processes such as shoot growth and nutrient uptake. Soil pH (9.78%)

and drainage (8.88%) received moderate importance, aligning with evidence that tea thrives in well-drained, slightly acidic soils. Factors such as land use/land cover, soil nutrients (N, P, K), and accessibility indices (distance from roads and rivers) scored much lower, highlighting their secondary role relative to broader climatic and topographic controls. The results indicate a broad consensus across the literature that tea land suitability is primarily governed by the presence of well-drained, slightly acidic soils, a balanced supply of essential nutrients particularly nitrogen, phosphorus, potassium, and organic matter as well as elevation-driven microclimates and slope-mediated drainage. Consequently, for land suitability assessments to be both reliable and robust, these factors must be given high priority and systematically integrated into evaluation frameworks.

3.5 Suitable conditions for tea cultivation

3.5.1 Overview

Suitability evaluation for tea cultivation is a critical step in ensuring both sustainable production and improved quality of tea, as it helps to prevent blind expansion into unsuitable areas and promotes long-term ecological balance (Xing et al., 2022). Tea crop is predominantly rainfed, and its performance is closely tied to a combination of soil, topographic, climatic, environmental, and accessibility conditions that shape the cultivation environment (Fernando et al., 2023). In this review, these influential factors are systematically explored with reference to suitability ratings reported in the literature, enabling a comprehensive synthesis of how soils, landforms, climatic regimes, and landscape accessibility interact to determine potential tea growing areas. This review considered ratings reported according to FAO (1976) guidelines, in which land suitability evaluation has four classes: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N). Beyond merely documenting these conditions, the review seeks to harmonize the variations across different studies, recognizing that location-specific parameters such as variety, microclimate, and socio-economic preferences often lead to some diverging interpretations of suitability. By integrating these perspectives, the discussion establishes a standardized yet flexible basis for defining optimal environments for tea cultivation that can be applied globally while taking into consideration location-specific suitability defining attributes for a detailed area-specific suitability assessment across various regions around the world.

3.5.1 Suitable soil conditions for tea cultivation

Soil characteristics are among the most decisive factors determining the ecological suitability of land for tea production. Tea (*Camellia sinensis*) requires soils that not only support vigorous root development but also maintain adequate aeration, nutrient availability, and moisture balance to enhance both yield and quality. The reviewed ratings of soil factors, in Table 3, as per FAO framework for land evaluation (highly suitable, moderately suitable, marginally suitable, and not suitable) provide critical thresholds that guide tea suitability assessment.

TABLE 2 Assigned AHP weights (in percentages) and their averages for key influential factors affecting tea cultivation.

Source	Assigned AHP weights in percentages (%)								Average weight
	Das et al. (2020)	Abdule and Woyesa (2023)	Chen et al. (2022)	Mallick et al. (2024)	Jayasinghe et al. (2019)	Xing et al. (2022)	Dolui (2024)	Pramanik (2016)	
Precipitation	23	23.9	15.77	6.84	25.4	–	–	–	18.98
Elevation	5	12.72	14.25	16.18	18.5	10	17.91	23.3	14.73
Slope	8	6.43	16.31	16.67	9	9.4	10.77	27.8	13.05
Temperature	15	3.42	15.77	7.06	21.4	12.4	10.61	–	12.24
Soil moisture	–	–	–	11.78	–	–	11.93	11.7	11.80
Soil pH	10	18.05	7.17	4.78	5.5	13.2	–	–	9.78
Drainage	19	3.42	–	–	3.6	–	–	9.5	8.88
Soil type	5	–	–	–	11.7	–	–	–	8.35
LULC	3	10.78	4.1	4.15	–	–	–	16.2	7.65
Potassium	–	–	2.03	–	–	12.1	–	–	7.07
Relative humidity	–	–	–	1.67	–	12.2	–	–	6.94
Aspect	–	9.07	6.22	–	–	10	3.66	2.4	6.27
Soil texture	5	6.96	–	8.05	2	–	–	–	5.50
Nitrogen	–	–	2.03	2.13	–	12	–	–	5.39
Distance from roads	2	–	–	1.1	–	2.1	13.69	1.9	4.16
Depth	–	5.25	–	–	2.8	–	–	–	4.03
Organic matter	–	–	3.6	5.05	–	2.5	–	–	3.72
Distance from rivers	3	–	–	3.01	–	1.1	3.62	–	2.68
Phosphorus	–	–	2.03	–	–	3	–	–	2.52
NDVI	2	–	1.37	1.45	–	–	–	–	1.61

Soil reaction (pH): it is the most influential determinant, given its strong control over nutrient availability and physiological functioning. Across most studies, the optimum range of 4.5–5.5 is consistently highlighted as highly suitable, as it enhances the uptake of essential nutrient elements including aluminium (Al) that contribute to growth of tea bushes and improved leaf quality (Das et al., 2020; Hajiboland, 2017; Mallick et al., 2024; Sahu et al., 2023). Tea is among the plants that are Al accumulator species, otherwise for the majority of plants this pH range is toxic (Hajiboland, 2017). Al accumulator species are plants capable of accumulating high concentrations of aluminium in their above-ground tissues without suffering from toxicity. Al bioavailability is high in highly acidic soils. Slight deviations into moderately acidic to near-neutral pH (5.5–6.5) fall under the category of moderately suitability. Beyond this range nutrient suppression occurs, and either alkalinity or extreme acidity (<4.0) compromises growth, ultimately reducing yield and affecting biochemical composition of polyphenols, amino acids and caffeine in leaves. The maintenance of this balance is therefore not only agronomic but also biochemical, shaping the quality attributes central to market competitiveness.

Soil organic matter: high soil organic matter (SOM >27 g/kg or SOC >7%) and soil organic carbon (SOC > 17–27 gm/kg is rated as

highly suitable and provides a reservoir of nutrients while improving soil structure (Chen et al., 2022; Mallick et al., 2024; Xing et al., 2022). Organic matter supports microbial activity, nutrient mineralization, and enhances soil physical structure, all of which are vital for sustainable tea growth (Chen et al., 2022; Mallick et al., 2024). Tea soils with sufficient soil organic carbon (SOC > 4%) produce vigorous branching and leaf development, directly influencing leaf quality and yield (Chen et al., 2022). SOM declines below 15 g/kg or SOC <4% (rated as marginally suitable) reduce microbial activity and nutrient availability, while critically low values (SOM <10 g/kg) are unsuitable for tea cultivation (Mallick et al., 2024).

Nitrogen, phosphorus, and potassium: macronutrients form the backbone of tea leaf production. Nitrogen levels >150 mg/kg, rated as highly suitable by Chen et al. (2022), stimulate continuous flushes of new shoots, ensuring high plucking potential and leaf biomass. Nitrogen deficiency leads to chlorosis and reduced yield (Mallick et al., 2024). Similarly, adequate phosphorus (>10 mg/kg) and potassium (>200 mg/kg) are essential for bud formation, leaf development, and biochemical quality (Chen et al., 2022; Xing et al., 2022). Deficiencies in these nutrients (as described by marginally and not suitable ratings) compromise both productivity

TABLE 3 Suitable soil conditions for tea growth.

Soil factor	Unit	S1	S2	S3	N	Reference
Soil pH		4.5–5.5	5.5–7.3	7.3–8.4	–	Das et al. (2020)
		4.5–5	5.1–6 & 4– 4.4	6.1–6.5 &<4	>6.5, &3.5	(Abdule and Woyesa, 2023)
		4.5–5.5	5.5–6	4.0–4.5	6–6.8	(Chen et al., 2022)
		4.5–5.0	5.1–6.0 & 4.4–4.0	6.1–6.5 & <4.0	>6.5	(Gahlod et al., 2017)
		4.5–5.5	5.5–5.6	5.6–6	0–4.5	(Mallick et al., 2024)
		4.5–5.5	5.5–7.2	<4.5	>7.2	(Jayasinghe et al., 2019)
		4.5–5.5	5.5–6.5	>6.5 & 4.0–4.5	–	(Xing et al., 2022)
		4.5–5.5	5.5–7.3	7.3–8.4		(Das et al., 2024)
SOM	(g/kg)	>27	20–27	15–20	5.0–15.0	(Chen et al., 2022)
	SOC (gm/kg)	17–27	10–17	27–40	0–10	(Mallick et al., 2024)
	%	7–16	4–7	3–4	–	(Xing et al., 2022)
N	mg/kg	>150	110–150	60–110	<60	(Chen et al., 2022)
	(cg/kg)	300–874	200–300	100–200	0–100	(Mallick et al., 2024)
	(mg/kg	2.2–2.8	>2.8	0–2.2	–	(Xing et al., 2022)
P	(mg/kg)	>30	20–30	10.0–20.0	<10	(Chen et al., 2022)
	(mg/kg)	>10	5–10	0–5	–	(Xing et al., 2022)
K	(mg/kg)	>200	120–200	80–120	<80	(Chen et al., 2022)
	(mg/kg)	>500	300–500	<300	–	(Xing et al., 2022)
EC	dS m-1	Non saline	<1.0	1.0–2.0	–	(Gahlod et al., 2017)
Soil texture		scl, l, cl, sl	c, sicl, sic	c(ss), ls, s	–	(Das et al., 2020)
		Loam, Loamy sand, Sandy, Sandy loam	Clay loam, Sandy clay, Silty clay, Sandy clay loam	Clay	Clay heavy	(Abdule and Woyesa, 2023)
		scl, l, cl, sl,	c, sicl, sic	c(ss), ls,s	–	(Gahlod et al., 2017)
		Fine-coarse loamy and Fine loamy	Coarse loamy-fine loamy	Coarse loamy	–	(Mallick et al., 2024)
		Loam/Organic	Silt loam/Heavy	Sandy loam/Medium	Clay, sandy/Light	(Jayasinghe et al., 2019)
		scl, l, cl, sl	c, sicl, sic	c(ss), ls, s	–	(Das et al., 2024)
Drainage		Moderately well drained to well drained	Imperfectly drained	Poorly drained	Very poorly drained	(Das et al., 2020)
		Excessive to moderate	Imperfect	Poor	Very poor	(Abdule and Woyesa, 2023)
		Moderately well drained to well drained	Imperfectly drained	Poorly drained	Very poorly drained	(Das et al., 2024)

(Continued)

TABLE 3 Continued

Soil factor	Unit	S1	S2	S3	N	Reference
Effective soil depth	(cm)	>150	100-150	100-50	<50	(Abdulle and Woyesa, 2023)
	(cm)	>150	100-150	50-100	<50	(Gahlod et al., 2017)
		– 0.90 to – 0.67	– 0.67 to – 0.54	– 0.54 to – 0.37	– 0.37–0.72	(Mallick et al., 2024)

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N, not suitable. N, soil properties – nitrogen; OM, organic matter; SOC, soil organic carbon; scl, sandy clay loam; cl, clay loam; sl, sandy loam; c, clay; sicl, silty clay loam; sic, silty clay; ls, loamy sandy; s, sand; c (ss), clay with sand streaks.

and the polyphenolic and caffeine content of tea, thereby reducing market quality.

Soil electrical conductivity (EC): tea plants are sensitive to salinity stress. Non-saline soils (<1.0 dS m⁻¹) are rated as highly suitable, while elevated EC (≥2.0 dS m⁻¹) reduces photosynthetic efficiency, chlorophyll content, and overall yield (Sahu et al., 2023). Thus, salinity management is critical in tea-growing areas, especially under irrigation.

Soil texture: this soil attribute influences water retention, drainage, and nutrient dynamics. Loamy soils—rated as highly suitable provide an ideal balance between aeration and moisture-holding capacity (Das et al., 2020; Mallick et al., 2024; Sahu et al., 2023). Tea grown on loamy soils exhibits enhanced water and nutrient uptake leading to higher concentrations of polyphenols, amino acids, and caffeine in leaves (Mallick et al., 2024). In contrast, clayey or sandy soils (rated as moderately suitable to marginally suitable) either restrict aeration or fail to retain adequate moisture, reducing suitability for tea production.

Drainage: adequate drainage is indispensable, with moderately well-drained to well-drained soils rated as highly suitable (Das et al., 2020, 2024). Waterlogging leads to root rot, nutrient loss, and reduced shoot development (Das et al., 2020; Sahu et al., 2023). Empirical evidence shows that improving drainage can enhance yields by 30–35% (Das et al., 2024). Poorly drained soils (rated as marginally suitable or not suitable) promote weed invasion and hinder root respiration, making them highly unsuitable for tea cultivation (Abdulle and Woyesa, 2023; Sahu et al., 2023).

Effective soil depth: deep soils (>150 cm, rated as highly suitable) support extensive root systems that optimize nutrient and water uptake (Gahlod et al., 2017; Abdulle and Woyesa, 2023). Deeper soils have been linked to greater shoot growth, leaf area, and higher catechin and caffeine concentrations in tea leaves (Sahu et al., 2023). Conversely, shallow soils (<50 cm, which is not suitable) restrict root expansion, making plants prone to drought stress and poor nutrient acquisition (Jayasinghe et al., 2019).

The review of the ratings illustrates that highly suitable soils for tea are characterized by moderately acidic pH (4.5–5.5), high organic matter content, sufficient NPK levels, loamy texture, well-drained deep profiles, non-saline conditions, and generally typical brown hill soils. Soils deviating from these thresholds fall into moderate or marginal suitability classes, often requiring corrective interventions such as organic amendments, drainage improvements, or pH regulation. Integrating these soil attributes ensures not only enhanced productivity but also sustains the chemical composition of tea, which is vital for both quality and market competitiveness.

3.5.2 Suitable topographic conditions for tea cultivation

Topography profoundly shapes the ecological niche for tea cultivation by mediating microclimatic conditions, soil formation processes, and hydrological dynamics that jointly determine growth, yield, and quality of tea crops. Among the most critical topographic factors are elevation, slope, aspect, hillshade, and landform type. The reviewed literature as summarized in Table 4 shows that the ratings demonstrate both similarities and

TABLE 4 Suitable topographic conditions for tea cultivation.

Factor	Unit	S1	S2	S3	N	Reference
Elevation	m	>15 m	10–15 m	7–10 m	<7 m	(Das et al. 2020)
	m	< 2000	2000–2500	>2,500	–	(Abdule and Woyesa, 2023)
	m	30–400	400–600	600–100	<30 & >1000	(Chen et al., 2022)
	m	300–582	150–300	100–150	49–100	(Mallick et al., 2024)
	m	500–700	300–500 and >700	0–300	–	(Xing et al., 2022)
	m	>15	10–15	7–10	<7	(Das et al., 2024)
Slope	degree (°)	5–25	<5	>25	–	(Das et al., 2020)
	%	< 13	13–25	25–55	>55	(Abdule and Woyesa, 2023)
	degree (°)	5–25	<5	25–35	>35	(Chen et al., 2022)
	degree (°)	5–13	3–5	1–3	0–1 & 13–41	(Mallick et al., 2024)
	degree (°)	5–25	0–5	>25	–	(Xing et al., 2022)
	degree (°)	5–25	<5	>25	–	(Das et al., 2024)
Aspect		[South, southeast, southwest]	[East, west, northeast, northwest]	[North]	–	(Abdule and Woyesa, 2023)
		[South, southeast, southwest]	[East, west, northeast, northwest]	[North]	–	(Chen et al., 2022)
	degree (°)	112.5–247.5	67.5–112.5 & 247.5–292.5	292.5–67.5 & –1–0	–	(Xing et al., 2022)
Landform		Pediment alluvial plain	Older flood plain, young alluvial plain	Flood plain, Dissected hill & valley	Water bodies	(Mallick et al., 2024)

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N, not suitable.

divergences, largely because of the tendency of authors to set suitability thresholds based on their local agro-ecological settings rather than making a reference from predetermined global standards. Normalizing these findings allows us to establish more coherent suitability ranges that can guide international tea suitability assessments.

Elevation emerges as the foremost topographic determinant of tea cultivation. Across studies, tea is reported to grow between sea level and about 2200 m though the highest quality tea is consistently associated with mid- to high-altitude regions (Das et al., 2020; Jayasinghe et al., 2019; Sahu et al., 2023). At higher elevations, reduced temperatures and higher humidity slow vegetative growth, leading to greater accumulation of biochemical compounds such as tannins, polyphenols, and aromatic oils that enhance tea quality (Mallick et al., 2024; Abdule and Woyesa, 2023; Sahu et al., 2023). Consequently, tea leaves from tea plants grown above 1000 m are often sweeter and more floral compared to those in the lowlands also as evidenced by Das et al. (2020), with elevated concentrations of bioactive volatiles including antioxidants and anti-inflammatory compounds (Abdule and Woyesa, 2023). However, excessively high elevations beyond 2500 m reduce yield because of colder soils and frost incidence (Jayasinghe et al., 2019). By contrast, low-lying plains below 200 m are unsuitable due to waterlogging and flooding risks (Jayasinghe et al., 2019; Mallick et al., 2024). Generally, a summary of the reviewed literature reveals that an elevation range of 1000–2000 m can be consistently classified as highly suitable for

tea cultivation, while the 600–1000 m range is regarded as moderately suitable. Elevation ranges of 300–600 m and/or 2500–3000 m are generally considered marginally suitable, whereas areas below 300 m and/or above 3000 m are deemed unsuitable. These threshold ranges capture the balance required to optimize both yield and quality, underscoring their broad applicability across diverse tea-growing regions around the world.

Slope also has a critical influence on tea suitability, primarily through its effects on drainage, soil erosion, and nutrient dynamics. The consensus from several authors is that gentle to moderately sloping land—generally 5–25° is ideal for tea cultivation (Chen et al., 2022; Das et al., 2020; Xing et al., 2022). Such slopes ensure proper drainage, prevent waterlogging, and promote nutrient cycling (Mallick et al., 2024; Sahu et al., 2023). Slopes flatter than 5° are prone to water stagnation, which negatively impacts root aeration, while excessively steep slopes above 25–30° induce severe soil erosion and landslide risks, limiting long-term sustainability (Fernando et al., 2023; Mallick et al., 2024). However, some localized findings extend highly suitable ranges to narrower bands, such as 5–13° (Mallick et al., 2024) or describe moderate suitability on slopes up to 25° (Fernando et al., 2023). Overall, the analysis and normalization of reviewed slope ratings suggest that, for global applicability, highly suitable slopes can be set at 5–20°, moderately suitable at 3–5° and/or 20–25°, marginally suitable at 1–3° and/or 25–35°, and not suitable at <1° (too flat, waterlogging) and/or >35° (too steep, erosion). This categorization reflects the balance

between optimal hydrological conditions and soil conservation requirements.

Aspect refers to the orientation of a slope in relation to the direction of incoming sunlight, which determines the amount of solar radiation the slope receives. The aspect of the slope regulates solar radiation and microclimatic regimes, influencing tea physiology and secondary metabolism. South-facing slopes in the Northern Hemisphere (and north-facing in the Southern Hemisphere) receive higher sunlight intensity, leading to faster growth and higher yields, but sometimes require supplemental irrigation to offset water stress (Chen et al., 2022; Sahu et al., 2023). In contrast, southeast- and southwest-facing orientations balance adequate light with moderated heat stress, making them consistently highlighted as highly suitable (Chen et al., 2022; Abdulle and Woyesa, 2023; Xing et al., 2022). On the other hand, north-facing slopes in the Northern Hemisphere and south-facing slopes in the Southern Hemisphere often support denser organic matter but lower solar radiation, reducing yield potential. A generalization from the reviewed literature suggests that, in the Northern Hemisphere, southeast-, south-, and southwest-facing aspects are highly suitable; east and west orientations are moderately suitable; northeast- and northwest-facing orientations are marginally suitable, while strictly north-facing slopes may be considered not suitable due to insufficient light for optimal tea physiology. In contrast, in the Southern Hemisphere, northeast-, north-, and northwest-facing aspects are highly suitable; east and west orientations are moderately suitable; southeast- and southwest-facing orientations are marginally suitable, while strictly south-facing slopes may be considered not suitable due to minimal light for optimal tea physiology.

Hillshade further refines aspect suitability by quantifying sunlight intensity over time. Studies show that moderate shading—whether from topographic positioning or interspersed shade trees, is most favourable for tea cultivation, as full exposure to intense sunlight stresses tea bushes and reduces leaf tenderness. Consequently, it is common practice in tea plantations to intersperse large shade trees among the tea shrubs, offering protection not only to the tea plants but also to the pickers. The optimal hillshade value corresponds to greyscale values of sun azimuth within the range of 23–68, which is most suitable for tea cultivation since this range reflects a balance of illumination, providing conditions that are neither excessively shaded nor overly exposed to sunlight (Dolui, 2024). This aligns with the agronomic practice of maintaining shade trees within plantations, both to safeguard tea physiology and to improve working conditions for pickers.

Landform type is another topographic factor governing suitability by determining drainage and soil water availability. Moderately sloped piedmont plains and undulating hilly terrain provide the most favourable balance, while water-stagnant depressions, floodplains, and excessively rugged high mountains are unsuitable (Mallick et al., 2024). Generally, literature indicates that tea plants thrive where topography permits steady drainage while minimizing both flooding and erosive losses.

The reviewed studies demonstrate considerable variation in how authors define and rate topographic suitability for tea cultivation, reflecting both subjective judgements and locally specific conditions. For instance, studies conducted in lowland areas such

as the Sylhet Division in northeastern Bangladesh, where elevations are generally below 335 m, considered tea cultivation suitable at elevations as low as 15 m (Das et al., 2020). In contrast, studies from highland regions including the Dabus Basin in southwest Ethiopia, Zhejiang Province in southern China, and Anhui Province in eastern China set much higher thresholds for highly suitable elevations, typically between 500 and 2000 m (Abdulle and Woyesa, 2023; Li et al., 2012; Xing et al., 2022). Such differences underscore the influence of localized climatic interactions, varietal adaptations, and historical land-use patterns on how suitability ranges are defined. For example, *C. sinensis* var. *sinensis* (China type) with adaptation to high-altitude agro-ecosystems, cooler environments and which produce superior quality attributes are well suited in highland areas, whereas *C. sinensis* var. *assamica* (Assam type) thriving in warm and humid tropical conditions can thrive well in lowland areas. More research should focus on resolving discrepancies arising from localised definitions of suitability by systematically testing these thresholds across a wider diversity of tea ecotypes and regions. The reviewed literature nonetheless provides an important foundation for establishing globally standardised ranges of suitability ratings for elevation, slope, aspect, and other critical topographic factors. These should be designed to reflect local contexts while being grounded in broader ecological principles. Future research should refine these standards further by integrating tea cultivar specificity, examining how changing climate will shift elevation limits upward, how slope-erosion interactions will affect sustainability in highland plantations, and how management interventions such as shading, terracing, or cultivar improvement might expand the marginally suitable zones. This approach will ensure that globally relevant standards are continuously updated, safeguarding the long-term adaptability, productivity, and quality of tea under changing environmental conditions. This is particularly necessary where trade-offs exist between yield-focused and quality-focused thresholds. Moreover, greater attention to the interactive effects of topography with soil and climate will be essential for developing a holistic land suitability framework capable of guiding sustainable expansion of tea cultivation worldwide.

3.5.3 Climatic factors

Climatic factors exhibit a profound influence on the growth, yield, and quality of tea, making them some of the most important determinants in the ecological suitability of tea cultivation. Table 5 presents a summary of suitability ratings of the reviewed climatic factors affecting tea cultivation. Precipitation emerges as the most widely discussed climatic factor, with authors generally agreeing that tea requires ample, well-distributed rainfall, although the exact ranges differ among studies. Some sources suggest that a minimum of 1000–1200 mm annually is necessary to sustain tea plants (Abdulle and Woyesa, 2023; Chen et al., 2022, 2025; Jayasinghe et al., 2019), while others emphasize that the optimal range for high yield and quality extends from 1800–2500 mm (Chen et al., 2022; Das et al., 2020; Rahaman and Aruchamy, 2022; Sahu et al., 2023). Still, more higher ranges, such as 2500–3000 mm (Jayasinghe et al., 2019) and even up to 3500 mm (Mallick et al., 2024), are reported as

TABLE 5 Suitable climatic conditions for tea cultivation.

Factor	Unit	S1	S2	S3	N	Reference
Precipitation	mm	>1800	1600–1800	1000–1600		(Das et al., 2020)
	mm	1800–2,000	1600–1,800	1000–1600	<1000	(Abdule and Woyesa, 2023)
	mm	>2350	2200–2350	2100–2200	<2100	(Chen et al., 2022)
	mm	1800–2000	1600–1800	1000–1600	< 1000	(Gahlod et al., 2017)
	mm	3000–3500	3500–3800	–	–	(Mallick et al., 2024)
	mm	>1800	1600–1800	1000–1600	–	(Das et al., 2024)
Temperature	°C	18–25	–	–	–	(Das et al., 2020)
	°C	18–25	26–28, 15–17	29–30, 13–14	>30, <13	(Abdule and Woyesa, 2023)
	°C	>22	21.5–22	21–21.5	<21	(Chen et al., 2022)
	°C	18–25	26–28, 15–17	29–30, 13–14	>30, <13	(Gahlod et al., 2017)
	°C	18–23	23–25	16–18	15.5–16	(Mallick et al., 2024)
	°C	17–20	>20	<17	–	(Xing et al., 2022)
	°C	18–25	–	–	–	(Das et al., 2024)
Sunshine hours	(h)	>1640	1620–1640	1580–1620	<1580	(Chen et al., 2022)
RH	(%)	>80	60–80	60–50	<50	(Gahlod et al., 2017)
	(%)	69.3–70.79	68–69.3	67.10–68		(Mallick et al., 2024)
	(%)	70–75	50–70	>75		(Xing et al., 2022)
Length of growing period	Days	>240	240–180	180–150	<150	(Gahlod et al., 2017)

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N, not suitable; RH, relative humidity.

optimal in certain tropical high-rainfall regions. These variations can be attributed to differences in local climatic conditions, soil drainage, and tea variety adaptability. For instance, in regions where soils drain rapidly, such as highland plantations, higher rainfall may be beneficial, while in lowland or poorly drained areas, such levels may cause waterlogging, root diseases, and soil erosion (Mallick et al., 2024; Sahu et al., 2023). Generalizing from these findings, a robust guide with wide applicability all over the world can be set whereby: highly suitable rainfall is set at 1200–2500 mm of annual rainfall with reliable distribution, moderately suitable at 800–1200 mm, marginally suitable at 600–800 mm, and not suitable at <600 mm or highly excessive >3500 mm depending on drainage constraints.

Temperature plays a similarly critical role, affecting both physiological processes and tea quality. Several studies converge on the range of 18–25 °C as the most ideal for growth and shoot elongation (Das et al., 2020, 2024; Gahlod et al., 2017), though some emphasize narrower ranges such as 19–23 °C (Chen et al., 2022; Jayasinghe et al., 2019; Wijeratne et al., 2007). Tea exhibits reduced shoot extension and yield when exposed to extremes below 13 °C or above 30 °C (Chen et al., 2022; Das et al., 2020; Jayasinghe et al., 2019), with prolonged exposure leading to water stress, leaf scorching, and decreased photosynthetic efficiency (Chen et al., 2025; Pramanik, 2016; Sahu et al., 2023). At excessively low temperatures, frost damage can cause severe crop losses and impair biochemical properties of the leaves (Chen et al., 2025), whereas high temperatures above 35 °C can accelerate evapotranspiration, promote pest and disease incidence, and suppress shoot growth (Chen et al., 2025; Sahu et al., 2023). These observations highlight both regional and

varietal differences and demonstrate how genetic variability dictates the response of tea to temperature. Consequently, highland tea varieties (*C. sinensis* var. *sinensis*) are often better adapted to cooler temperature ranges and produce finer aromatic profiles, while lowland varieties (*C. sinensis* var. *assamica*) tolerate slightly higher temperatures. Harmonizing the evidence from the reviewed studies, a robust guide with wide applicability all over the world can be set whereby; highly suitable temperature is set at 18–25 °C, moderately suitable at 15–17 °C and/or 26–28 °C, marginally suitable at 13–14 °C and/or 29–30 °C, and not suitable at <13 °C and/or >30 °C.

Sunshine duration is another factor with considerable influence on both growth and quality of tea. Evidence suggests that annual sunshine hours exceeding 1640 h is highly suitable, whereas levels between 1580 and 1620 h are marginal (Chen et al., 2022). However, much prolonged strong solar radiation can raise leaf temperatures, leading to reduced photosynthetic efficiency and yield (Chen et al., 2025; Jayasinghe et al., 2019). Nonetheless, moderate sunshine enhances the synthesis of amino acids, which improve the flavour and quality of green teas (Tang et al., 2015). Thus, while adequate sunshine is vital for sustained photosynthesis, excessive and prolonged insolation requires moderating strategies such as agroforestry or shade trees. Generally, reviewed literature shows that highly suitable sunshine duration is set at >1640 hours annually, moderately suitable at 1620–1640 hours annually, marginally suitable at 1580–1620 hours annually, and not suitable at <1580 hours annually.

Relative humidity (RH) also plays a crucial role in influencing transpiration and nutrient accumulation. Studies suggest that RH

>80% promotes lush growth and high-quality leaf production (Gahlod et al., 2017), while moderately suitable conditions occur between 60–80% (Gahlod et al., 2017; Mallick et al., 2024). Values below 50% cause excessive transpiration and leaf desiccation (Xing et al., 2022). However, some findings indicate that RH levels above 75% may foster fungal diseases if sustained (Mallick et al., 2024). These differences point to the importance of balancing moisture availability with disease management, and thus the ideal window lies around 70–80%.

The length of the growing period (LGP) is another important climatic factor as it provides a holistic measure of climatic suitability, integrating temperature and moisture availability. A duration of more than 240 days annually is classified as highly suitable (Gahlod et al., 2017), since it ensures multiple plucking rounds and consistent shoot flushes. Gahlod et al. (2017) further adds that areas with 180–240 days fall under moderate suitability, while those with less than 150 days cannot sustain meaningful tea production. This factor highlights why equatorial regions like Kenya and Sri Lanka, with year-round tea growth, outperform seasonal regions in productivity and supply reliability.

The reviewed literature indicates that variations in geography, topography, soil types, and inherent tea varietal properties strongly influence the suitability of climatic factors such as rainfall, temperature, and relative humidity, leading to differences in the threshold values reported across regions. For example, studies in humid lowland tropics report higher optimal rainfall thresholds than those in subtropical highlands. Further, studies from China tend to emphasize narrower temperature ranges, which might be due to the sensitivity of their local cultivars to frost and heat stress. The literature also demonstrates that genetic variability strongly affects the response of tea to climatic factors such as temperature and rainfall. Highland varieties are often associated with high tolerance for cooler climates, whereas lowland varieties are often associated with humid tropical climates. Incorporating varietal considerations

into climate suitability assessments is essential for aligning tea genotypes with site-specific conditions and optimizing both productivity and sustainability. The reported suitability ratings therefore need to be converged and harmonized into meaningful standards with wider global applicability. Future research should refine these ranges considering varietal adaptability, climate change impacts, and the interactions of climatic factors with soil and topography. For instance, drought-resilient varieties may expand the lower precipitation limit, while shade management strategies may alter sunshine thresholds. Similarly, anticipated shifts in rainfall distribution and temperature regimes under climate variability underscore the necessity of continuous calibration of suitability standards to safeguard both the productivity and quality of tea worldwide.

3.5.4 Environmental surface and land cover factors

The suitability of land for tea cultivation is strongly correlated with environmental conditions, particularly land use/land cover (LULC) and vegetation indices such as the normalized difference vegetation index (NDVI) (Abdulle and Woyesa, 2023; Chen et al., 2022; Das et al., 2020, 2024; Mallick et al., 2024). These parameters not only determine the physical availability of land for tea estates but also reflect the ecological productivity and vigour of vegetation, which are essential for sustaining tea as a perennial crop. In the case of LULC, based on the ratings compiled from different studies as summarized in Table 6, tea plantations and forested landscapes consistently emerge as the most highly suitable land cover classes, while settlements, rivers, wetlands, and built-up areas are considered not suitable for tea cultivation (Abdulle and Woyesa, 2023; Chen et al., 2022; Das et al., 2020, 2024; Mallick et al., 2024). This classification is grounded in the understanding that forests and existing tea estates are indicative of ecosystem baseline for

TABLE 6 Suitable environmental surface and land cover factors for tea cultivation.

Factor	S1	S2	S3	N	Reference
LULC	Tea estates	Forest	High agricultural land	Settlements, water bodies, rivers, and wetlands	(Das et al., 2020)
	Tea plantation/Forest	Cropland	Farmland	Building area/water body	(Abdulle and Woyesa, 2023)
	Tea plantation	Forest	Farmland	Building land/water body	(Chen et al., 2022)
	Tea plantation	Vegetation cover	Agricultural land	River, sand, built-up area	(Mallick et al., 2024)
	Tea estates	Forest	High agricultural land	Settlements, water bodies, rivers, and wetlands	(Das et al., 2024)
NDVI	>0.6	0.4–0.6		0.4 <0	(Das et al., 2020)
	>0.6	0.4–0.6	0–0.4	<0	(Chen et al., 2022)
	0.65–0.90	0.48–0.65	0.30–0.48	– 0.69 to 0.30	(Mallick et al., 2024)
	>0.6	0.4 - 0.6		0.4 <0	(Das et al., 2024)

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N, not suitable.

favourable soil fertility, shade patterns, and microclimatic buffering, whereas agricultural croplands and high agricultural lands are indicative of moderate tea suitability (S2–S3) (Chen et al., 2022; Abdule and Woyesa, 2023), largely due to competition with other crops, degradation from intensive cultivation, or limited capacity for perennial rooting systems.

LULC thus serves as both a proxy and a determinant of ecological resilience in tea-growing areas. Forests and vegetative cover improve soil organic matter and regulate water availability, thereby ensuring sustainable productivity, while agricultural fields converted into tea estates may initially show moderate suitability until they stabilize into perennial systems. Furthermore, some differences across studies were observed. For instance, cropland (which also was classified as highly agricultural land) was placed under moderately suitable class by Abdule and Woyesa (2023), but in other studies this was rated as marginally suitable class (Das et al., 2020, 2024; Mallick et al., 2024). This could be explained by the variability of the study areas. Studies conducted in highland regions with rich forest soils may classify cropland as marginally suitable due to soil erosion risks, while in a lowland region with fertile alluvial soils, the same cropland may be seen as moderately suitable. A general view from the literature is that highly suitable (S1) lands for tea are those under forest, bushland or existing tea cover, moderately (S2) lands include mixed cropland and semi-natural vegetation, marginally suitable (S3) lands include intensively cultivated farmland or degraded lands, and not suitable (N) lands are occupied by settlements, water bodies, and wetlands that are physically unsuitable for perennial plantation establishment.

The role of NDVI as an indicator of suitability is equally critical because it directly measures the density and vigour of photosynthetically active vegetation, thus reflecting the growing environment available for tea. High NDVI values above 0.6 are consistently classified as highly suitable (Chen et al., 2022; Das et al., 2020, 2024; Mallick et al., 2024), indicating dense, healthy vegetation cover, which correlates with greater canopy vigour, better root establishment, and favourable microclimates for tea growth. Moderately suitable conditions fall within the NDVI range of 0.4–0.6 (Chen et al., 2022; Das et al., 2020, 2024), where vegetation cover is present but not at optimal density, while marginal lands show NDVI values as low as 0.3–0.4 (Chen et al., 2022; Das et al., 2020, 2024), indicating sparse vegetation cover, higher susceptibility to soil exposure, and reduced biomass potential. Negative NDVI or

values approaching zero correspond to built-up or waterlogged areas (Chen et al., 2022; Das et al., 2020, 2024; Mallick et al., 2024), reflecting unsuitability. Vegetation indices including NDVI are highly indicative of tea land suitability because higher NDVI reflects robust green biomass, which ensures canopy shade, reduced soil temperature fluctuations, and enhanced organic matter cycling, all of which contribute to improved tea leaf vigour and quality, as well as resilience against stress. Future research could aim to refine these ratings by integrating temporal NDVI variations with tea phenology, since tea exhibits seasonal flushes of growth that may affect vegetation vigour indices. Similarly, studies need to account for the conversion potential of moderately suitable croplands into perennial tea estates under long-term management. More comparative studies across a wide range of altitudinal gradients and climatic zones are also required to calibrate NDVI thresholds for different tea varieties, as some cultivars thrive under lower canopy densities while others require dense shade. By addressing these gaps, global suitability assessments will achieve greater consistency and predictive power for guiding tea expansion and sustainable management worldwide.

3.5.5 Accessibility factors

Accessibility is one of crucial determinants of suitability for tea cultivation, as it affects not only the ease with which inputs are delivered and outputs are transported, but also the efficiency of irrigation, availability of labour, and the proximity to processing facilities. Tea, being a highly perishable crop, requires that fresh leaves reach factories within a short period after harvesting to maintain quality, making accessibility parameters such as distance from roads, rivers, lineaments, water bodies, and settlements fundamental in determining suitability for cultivation. Distance from roads (Table 7) emerges as one of the most significant accessibility factors. Across reviewed studies, land that lies within 0–1 km of a road is rated as highly suitable (Das et al., 2020, 2024; Mallick et al., 2024; Xing et al., 2022), while 1–2 km is moderately suitable (Das et al., 2020, 2024), 2–4 km is marginally suitable (Das et al., 2020, 2024), and any distance beyond 4 km is considered unsuitable (Das et al., 2020, 2024) when evaluating accessibility. Some authors, however, provide narrower thresholds, with Xing et al. (2022) suggesting 0–0.5 km as highly suitable, 0.5–0.8 km as moderately suitable, 0.8 – 1.2 km as marginally suitable and

TABLE 7 Suitable accessibility conditions for tea cultivation.

Factor	Unit	S1	S2	S3	N	Reference
Distance from roads	km	0–1	1 – 2	2 – 4	>4	(Das et al., 2020)
	meter	–	1500–3000	3000–5000	5000–5675	(Mallick et al., 2024)
	km	0–0.5	0.5–0.8	0.8–1.2	>1.2	(Xing et al., 2022)
	km	0–1	1.0–2	2.0–4	>4	(Das et al., 2024)
Distance from rivers	km	0–0.5	0.5–1	1.0–2	>2	(Das et al., 2020)
	meter	0–500	500–1500	1500–3000	3000–12362	(Mallick et al., 2024)
	km	0.2–0.5	0–0.2	0.5–1.0	>1.0	(Xing et al., 2022)
	km	0–0.5	0.5–1	1.0–2	>2	(Das et al., 2024)

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N, not suitable.

distances greater than 1.2 km as unsuitable. Mallick et al. (2024), on the other hand, provide slightly broader thresholds in meters, classifying 1500–3000 m as moderately suitable, 3000–5000 m as marginally suitable and beyond 5000 m as unsuitable. These differences could be attributed to the variations in road network density, terrain, and infrastructure in the respective study areas. In mountainous or remote regions where road access is limited, longer distances might not be tolerated, whereas in more connected lowland areas, to some extent longer distance thresholds might be justified. Nonetheless, according to Mallick et al. (2024) and Xing et al. (2022) shorter distances ensure efficient leaf transport, lower input costs, and reduced spoilage due to the perishable nature of tea leaves. In this regard, rational road proximity suitability recommendations from the reviewed literature might place distances within 0–1 km in highly suitable class (S1), 1–2 km in moderately suitable (S2), 2–4 km in marginally suitable class (S3), and anything beyond 4 km in unsuitable class (N).

Distance from rivers also plays an important role, not only as a source of irrigation water but also for enhancing soil fertility in riparian zones. Das et al. (2020) and Das et al. (2024) suggest that tea plantations within 0–0.5 km of rivers are highly suitable, while those between 0.5–1 km are moderately suitable, and beyond 2 km unsuitable. Mallick et al. (2024) extends this distance to 3000 m before considering land unsuitable, whereas Xing et al. (2022) considers areas as close as 0–0.2 km to be only moderately suitable, and 0.2–0.5 km as highly suitable, suggesting local adaptations due to flood risks. The observed inconsistencies in the reviewed literature could be stemming from differences in hydrological regimes: in flood-prone lowlands, extreme proximity to rivers may expose tea to inundation, while in semi-arid regions, closeness to rivers is a critical advantage for irrigation. Thus, suitability recommendations on proximity to rivers should balance the dual function of rivers as irrigation sources and potential flood hazards to align with most of the evidence.

Other accessibility factors, though less frequently discussed, are also relevant. Distance from lineaments has hydrological importance since lineaments act as groundwater channels; high lineament density zones have been shown to support tea plantations with better water availability (Dolui, 2024). Similarly, proximity to water bodies ensures adequate soil moisture and irrigation, though excessively close distances may lead to waterlogging (Xing et al., 2022). Distance from settlements also has critical implications for tea suitability. Since tea harvesting is highly labour-intensive and predominantly undertaken by skilled female workers, closeness to settlements enhances labour availability, reduces travel time, and ensures timely plucking (Dolui, 2024). Thus, plantations near villages are more suitable than those at greater distances due to the ready supply of labour, while distant plantations face labour shortages and logistical inefficiencies. This makes settlement proximity a vital but often underemphasized criterion in accessibility assessments. More work is needed to quantify the trade-offs between proximity to rivers and flood risk, or closeness to roads and the effect of pollution on tea quality. Similarly, region-specific studies comparing the labour dynamics linked to settlement proximity would improve the understanding of socio-economic factors in accessibility. Integrating accessibility with topography and

climatic suitability would also enhance the development of holistic, globally recommended suitable accessibility conditions for tea cultivation.

3.6 Implications of environmental suitability on tea yield and quality

The synthesis of reviewed studies demonstrates that tea yield is strongly controlled by the interaction of climatic, edaphic, and topographic factors, which collectively determine growth conditions and biomass accumulation. Optimal temperature ranges, well-distributed rainfall, and suitable elevation regimes enhance vegetative growth, while soil properties such as pH, organic matter content, nutrient availability, and drainage status regulate root development and nutrient uptake efficiency (Abdulle and Woyesa, 2023; Chen et al., 2022, 2025; Das et al., 2020, 2024; Gahlod et al., 2017; Jayasinghe et al., 2019; Mallick et al., 2024; Xing et al., 2022; Wijeratne et al., 2007). Topographic attributes, particularly slope and aspect, further influence microclimatic conditions and water movement, thereby affecting plant performance (Abdulle and Woyesa, 2023; Chen et al., 2022; Das et al., 2020, 2024; Jayasinghe et al., 2019; Mallick et al., 2024; Sahu et al., 2023; Xing et al., 2022). In addition, land cover and management-related factors contribute to modifying local environmental conditions that support sustained productivity (Das et al., 2024; Mallick et al., 2024).

Beyond these environmental controls, tea performance is also fundamentally shaped by its inherent genetic variability. Tea (*Camellia sinensis*) comprises a broad genetic pool that enables adaptation across diverse agro-ecological settings. The *C. sinensis* var. *sinensis* (China type) is typically suited to cooler highland environments, and *C. sinensis* var. *assamica* (Assam type) (Mondal et al., 2004; Wambulwa et al., 2016). In addition, extensive hybridization and selection have produced cultivars with improved yield potential, stress tolerance, and quality characteristics. This genetic diversity governs how tea responds to environmental gradients such as temperature, rainfall, elevation, and soil conditions. For instance, the China type is often associated with high-altitude agro-ecological settings and enhanced quality attributes, whereas the Assam type is predominant in lowland regions due to its vigorous growth and relatively higher productivity (Ahmed et al., 2019). Consequently, integrating varietal differentiation into land suitability frameworks is essential to match appropriate genotypes with site-specific conditions, thereby optimizing both productivity and long-term sustainability. These findings indicate that high-yielding tea agro-ecological settings are typically associated with environments where these factors co-exist within optimal thresholds, highlighting the importance of integrated, multi-criteria approaches in land suitability evaluation for maximizing tea productivity.

In addition to yield, tea quality is a critical component of land suitability, as it determines market value and consumer acceptance. Tea quality is largely governed by biochemical constituents such as polyphenols, catechins, caffeine, and amino acids, which are strongly influenced by environmental conditions (Ahmed et al., 2019; Hu et al., 2024; Wu et al., 2025; Xie, 2024). Altitude, temperature, and moisture regimes play a key role, with highland

environments generally producing superior flavour and aroma due to slower growth and enhanced accumulation of secondary metabolites (Abdulle and Woyesa, 2023; Chen et al., 2025; Hu et al., 2024; Mallick et al., 2024; Sahu et al., 2023; Xie, 2024). Soil properties, including pH and organic matter content, further influence leaf chemistry and sensory attributes (Wang et al., 2023). Conversely, environmental stress may negatively affect quality by disrupting biochemical balance. Accordingly, land suitability evaluations should integrate both productivity and quality parameters to ensure that identified areas support high-value tea production systems.

3.7 Validation

Validation is a critical step in multi-criteria land suitability assessment because it ensures that the spatial models reflect actual conditions on the ground and can be trusted for guiding agricultural planning. In the context of tea cultivation, validation helps to verify whether model outputs generated through approaches such as AHP, LESE, DEMATEL, or advanced machine learning techniques correspond with the real distribution of tea estates and their performance. Many studies have ignored this important stage, often due to inadequate access to ground reference information, such as GPS-located plantation boundaries and yield statistics. Others have failed to take advantage of freely available remote sensing resources like Landsat or Sentinel imagery, which provide imagery for deriving vegetation indices such as NDVI and LAI that could serve as proxy validation datasets when direct yield or ground-based data are not accessible.

Among the most widely employed validation strategies is the use of ground reference data, particularly GPS points collected during field surveys. For instance, Das et al. (2020) collected GPS coordinates of tea estate locations and overlaid them with suitability maps derived from AHP analysis. The degree of overlap between actual tea plantation boundaries and the highly or moderately suitable classes provided an empirical basis for confirming the model's accuracy. Similarly, a tea land suitability study by Li et al. (2012) in Zhejiang Province, China, used a large dataset of over 3,700 GPS points to test the LESE model's predictions. The findings revealed that nearly 88% of sampled points fell within highly and moderately suitable zones, closely matching the actual planting distribution and underscoring the method's reliability. These GPS-based approaches enhance methodological clarity because they draw on direct field observations, allow explicit estimation of sampling error, and when combined with spatial blocking, help to reduce bias from spatial autocorrelation. These validation techniques not only enhance confidence in model outputs but also highlights their potential utility for policy-making and regional land-use planning. However, they also require field access and careful sampling design, as clustered or convenience-based points can exaggerate model performance.

Another important method involves integrating agronomic performance data with vegetation indices derived from satellite imagery. For instance, Das et al. (2020) integrated yield data from

the Bangladesh Tea Board with NDVI and LAI values extracted from Sentinel-2 imagery during active growing seasons to test the validity of suitability assessments. This integration of ground-based productivity data with remotely sensed crop vigour metrics offers a powerful dual-check mechanism. It confirms whether predicted suitable areas indeed produce higher yields and more robust vegetative growth, thereby insisting model reliability. Generally, when combined, yield records and spectral indices capture both the spatial distribution of tea and its physiological performance, offering a more comprehensive benchmark for evaluating suitability maps than occurrence data alone.

Overlay analysis in GIS has also been used, particularly in large-scale assessments whereby tea suitability maps have been overlaid with existing land use/land cover maps. In a study by Jayasinghe et al. (2019) in Sri Lanka, land use maps of existing tea-growing areas were intersected with suitability classes derived from AHP analysis. A high percentage of overlap between actual plantations and highly suitable classes indicated model validity. Similarly, in Darjeeling, India, researchers validated AHP and MIF outputs by intersecting suitability maps with land use data and verifying with Google Earth imagery; GPS-based ground-truthing further strengthened these validations, as 22 estates were directly checked against predicted suitability zones in the same study (Dolui, 2024). The extent of overlap quantified the degree to which modelled “suitable zones” aligned with existing estates. This approach is appealing because it is transparent, easy to reproduce in any GIS tool, and relies only on a validated reference layer alongside the predicted map. Its limitations are equally evident: it evaluates agreement with existing patterns rather than true agronomic potential and can be influenced by policy choices, land tenure systems, or historical decisions that located tea where it was convenient rather than where it was most biophysically suitable. Also, this validation approach is effective only where tea estates are already well established but proves impractical in potential areas for tea cultivation in which plantations have not yet been established. Even so, as an initial validity check, map–overlay coincidence remains the most practical and accessible starting point.

Advancements in statistical and machine learning methods have introduced additional validation possibilities. Random Forest (RF) and Logistic Regression (LR) models applied in Darjeeling Himalaya, India, demonstrated strong predictive accuracy through interpretation of the receiver operating characteristic—area under curve (ROC-AUC) values (Sahu et al., 2023). The use of ROC curves provided a quantitative, standardized metric for assessing classifier performance; whereby RF outperformed LR. These results confirmed that machine learning could reliably categorize tea-growing zones. Such approaches suggest the growing potential of models like Support Vector Machines (SVM), k-Nearest Neighbors (kNN), Artificial Neural Networks (ANN), or Convolutional Neural Networks (CNN) for even more robust suitability modelling and validation. Suitability maps are typically ordinal (e.g. discrete suitability classes of S1, S2, S3 and N), whereas many machine learning workflows validate against binary presence/absence or presence/background data. In such cases, careful thresholding—

such as using Youden's J or prevalence-based rules is required to translate continuous probabilities into discrete suitability classes. Strong validation practice goes beyond single holdouts, employing k-fold or spatially blocked cross-validation to minimise spatial leakage. Metrics such as confusion matrices, sensitivity, specificity, and precision–recall are valuable complements to AUC, particularly when prevalence is low. These statistical validations are powerful because they quantify generalization error, but they also demand rigorous data curation and careful experimental design. Their reliability ultimately depends on transparent documentation of sampling strategies, threshold choices, and the mapping of probabilistic outputs to suitability classes.

Another less highlighted but important aspect of validation in AHP-based studies is the consistency ratio (CR). While primarily used to test the logical consistency of pairwise comparisons, CR indirectly validates the credibility of the weighting process (Abdulle and Woyesa, 2023; Chen et al., 2022; Das et al., 2020; Dengiz et al., 2020; Dolui, 2024; Jayasinghe et al., 2019; Mallick et al., 2024; Rahaman and Aruchamy, 2022). A model with a low CR ensures that expert judgments are coherent, thereby lending more confidence to subsequent suitability outputs. Thus, CR is a necessary safeguard before any external geographic validation proceeds. When combined with spatial or statistical validation approaches, CR offers a methodological safeguard against bias in criteria weighting. It is important to note that CR only certifies the reliability of judgments, not the empirical correctness of the spatial predictions; it must therefore be coupled with the overlay, GPS, or performance-based validations described above to complete the evidentiary chain from reasoning, to mapping, to real-world situation.

Overall, the literature underscores that validation of tea suitability assessments should not rely on a single method but rather on a combination of complementary approaches. Yield data, when available, remain the gold standard for verifying suitability predictions, though they must be used alongside vegetation indices to capture temporal crop variability (Das et al., 2020). In contexts where yield or GPS data are scarce, vegetation indices like NDVI, LAI, Enhanced Vegetation Index (EVI), or even phenology-based indices provide practical alternatives for cross-checking suitability maps. At the same time, the underutilization of machine learning methods suggests a gap that future research could address by systematically comparing models such as RF, SVM, ANN, and CNN across different agro-ecological settings, using complementary metrics such as AUC, confusion-matrix-based measures (e.g., user's and producer's accuracies), and other threshold-dependent indicators. This would help identify the most reliable techniques for validating complex, multi-criteria land suitability models. A stronger culture of validation drawing on both field-based and remote sensing data, reinforced with statistical rigor will be indispensable in producing credible, transferable, and policy-relevant land suitability assessments for tea cultivation. Furthermore, data sharing in tea suitability studies will strengthen validation by reducing heterogeneity, enabling reproducibility, and ensuring robust, policy-relevant agronomic assessments.

4 Conclusion

This review focused on criteria for consideration in assessing land suitability for tea cultivation. The review reveals that, the global literature on land suitability assessment remains geographically fragmented, with most studies concentrated in Asia, Middle East and East Africa, leaving Latin America and North America under-represented. This reflects the location-based variability in tea cultivation preferences and the crop's high degree of agro-ecological selectivity, which restricts its cultivation to a limited number of suitable regions worldwide. The factors consistently identified as most influential for tea cultivation encompass soil-related attributes (soil pH, soil moisture, drainage, soil texture, effective depth, soil type, soil organic matter, and N, P, K nutrients), topographic factors (elevation, slope, and aspect), climatic factors (precipitation, temperature, and relative humidity), land cover and surface environmental indicators (LULC and NDVI), as well as accessibility factors (proximity to roads and rivers). A synthesis of the most influential determinants in multi-criteria frameworks from the literature reveals 20 key factors, ranked in order of influence from highest to lowest as follows: precipitation, elevation, slope, temperature, soil moisture, soil pH, drainage, soil type, LULC, potassium, relative humidity, aspect, soil texture, nitrogen, distance from roads, soil depth, organic matter, distance from rivers, phosphorus, and NDVI. A summary of suitability conditions reveals that highly suitable conditions for tea cultivation are characterized by moderately acidic pH (4.5–5.5), well-drained, nutrient-rich loamy soils; elevation range of 1000–2000 m which balance yield with quality; slopes of 5–20° that enhance drainage without excessive erosion; and favourable slope aspects—south- to southeast-facing in the Northern Hemisphere and north- to northeast-facing in the Southern Hemisphere—that optimize solar radiation and microclimates. Climatic thresholds converge around annual precipitation of 1200–2500 mm with reliable distribution, mean annual temperatures of 18–25 °C, sunshine exceeding 1640 hours annually, relative humidity between 70–80%, and a growing period longer than 240 days. Beyond these thresholds, suitability declines from moderate to marginal before becoming unsuitable. Environmental settings where forests or existing tea plantations dominate land cover and NDVI values exceed 0.6 consistently emerge as highly suitable, whereas wetlands, water bodies, and built-up areas are not suitable for perennial tea establishment. Accessibility factors also demonstrate a clear suitability for cultivation, with lands located within 1 km of roads and 0–0.5 km of rivers being highly suitable, while distant or flood-prone sites are unsuitable. However, inconsistencies in these thresholds across studies were observed often reflecting local context, varietal differences, and methodological choices rather than universal standards. To achieve globally harmonized criteria, future research should focus on integrating diverse datasets including field surveys, remote sensing, and IoT-based monitoring within standardized frameworks that allow cross-regional comparison, while strengthening validation through the combined use of ground reference data, yield statistics, vegetation indices, and advanced machine learning approaches. Equally, greater inclusivity

in research coverage, particularly in underrepresented regions, alongside closer attention to interactions among soil, topography, climate, and management interventions, will be vital to develop globally applicable suitability standards that support sustainable expansion, safeguard tea quality, and enhance resilience under climate change.

Data availability statement

The original contributions presented in the study are publicly available. This data can be found here: Mendeley Data, <https://doi.org/10.17632/GGHR5B5326>.

Author contributions

FM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. BM: Data curation, Supervision, Writing – review & editing. HS: Data curation, Supervision, Writing – review & editing. BM: Data curation, Methodology, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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