Experimental Agriculture (2026), vol. 62, e9, 1–16
doi:10.1017/S0014479726100313

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Land suitability evaluation for citrus cultivation in southeastern Hubei, China, based on integrated AHP-GIS and fuzzy mathematical methods

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(Received 14 December 2025; revised 12 March 2026; accepted 10 April 2026)

Abstract
The citrus industry is vital to regional economies, and scientific land suitability evaluation is essential for spatial optimisation. This study focuses on Tongcheng County in Hubei Province, which exemplifies a typical red soil hilly region that is ecologically vulnerable in southeastern China. This study integrates Geographic Information System (GIS), Analytic Hierarchy Process (AHP), and fuzzy mathematics to develop a comprehensive land suitability evaluation model that balances factor continuity with evaluation uncertainty. Multi-source spatial data (climate, topography, soil) were used to quantify fuzzy membership functions for citrus growth. Subsequently, we conducted a weighted overlay analysis based on this quantification, which resulted in the creation of a citrus cultivation suitability evaluation map for Tongcheng County. The evaluation results categorised the study area into three distinct zones: (1) The Optimal Zone (CAI $\geq$ 0.75), which comprises 75.8% (857 km^2) of the total study area; (2) The Suitable Zone (0.55 $\leq$ CAI $\leq$ 0.75), which constitutes 19.6% (222 km^2) of the total study area; and (3) The Unsuitable Zone (CAI $\leq$ 0.55), which represents 4.6% (52 km^2) of the total study area. The research findings aligned with the actual conditions in Tongcheng County, thereby confirming the feasibility of the employed research methodology. These outcomes address research gaps and provide a replicable methodological framework for land evaluation in mountainous regions. This approach can be directly utilised in local agricultural spatial planning and the development of land-use policies. It carries substantial practical implications for advancing sustainable agricultural development and revitalising rural areas in mountainous regions.

Keywords: Analytic Hierarchy Process (AHP); Geographic Information System (GIS); fuzzy mathematics; citrus; land suitability evaluation

Introduction

Citrus cultivation is prevalent worldwide. As a significant centre of origin, China's citrus cultivation expanded from 21,759.5 km^2 in 2013 to 29,958.1 km^2 in 2022 (37.68% increase). Output value rose from $12.8 billion to $28.1 billion (118.91% growth) (Dong *et al.*, 2024). Consequently, China has become the world's largest producer of citrus. This fruit is extensively cultivated throughout the country, particularly in southern China, where it occupies the largest cultivation area among fruit trees and holds significant economic importance. In southern China, citrus occupies the largest cultivation area among fruit trees and holds major economic importance (Zhong and Nicolosi, 2020). Hubei Province, a significant region for citrus cultivation, has a citrus cultivation area of 2,430.67 km^2, which constitutes 59% of the province's total fruit cultivation area. Tongcheng County in Hubei Province is recognised as both the primary production area and an industry benchmark for premium citrus in southeastern China. However, beneath this prosperity exist several issues that demand immediate attention and resolution. Challenges in Tongcheng County include weak management, extensive cultivation, and soil degradation. These issues contribute to a decline in quality and a diminished resilience to risks (Hossain *et al.*, 2020). In the hilly red soil regions of southern China, ecological degradation represents a significant and pressing challenge. These areas suffer severe erosion, soil and water loss, and ongoing ecological decline (Li *et al.*, 2020). Consequently, the citrus industry lacks a scientific and refined land suitability evaluation system essential for planning and development. This deficiency misaligns industrial layout with land resources, causing cascading problems (Tercan and Dereli, 2020). To optimise the layout of the citrus industry in Tongcheng County, it is essential to conduct a scientific land suitability evaluation and accurately delineate optimal production zones.

Land suitability evaluation systematically assesses land appropriateness, identifying suitability classes, spatial distribution, and limiting factors (Mugiyo *et al.*, 2021). Selecting an appropriate land suitability evaluation method is therefore essential. Traditional approaches rely on field surveys and qualitative descriptions, which are time-consuming and unsuitable for large-scale dynamic assessments (Abuzaid *et al.*, 2025). In recent years, GIS technology has found extensive application in land suitability evaluation (Bhat *et al.*, 2023). Owing to its robust capabilities in spatial data management, analysis, and visualisation (Chatrabhuj *et al.*, 2024). GIS integrates and analyses multidimensional geospatial data, offering strong support for land suitability assessments (Kalogirou, 2002). The integration of fuzzy mathematics into land suitability evaluation is regarded as having considerable potential for practical application (Pilevar *et al.*, 2020). D'Antonio et al. (2025) utilised AHP and fuzzy logic alongside GIS technology in Matera, Italy, to assess the suitability for grapevine cultivation. Almayyahinormal Al-Atab (2024) integrated Fuzzy-AHP with GIS to map suitable and unsuitable zones for wheat in Basra, Iraq, and to isolate key limiting factors. Singha *et al.* (2023) employed Fuzzy-AHP to assess land suitability for rice and potato in West Bengal, India, using 21 parameters and validating outputs with Random Forest and SVM models. Kılıc *et al.* (2022) applied a similar fuzzy-AHP-GIS framework for high-resolution wheat suitability mapping in Turkey's Tozanlı Sub-basin. This approach aims to support sustainable agricultural land-use planning in the region. The citrus-growing areas in southeastern China exhibit characteristics such as complex and diverse terrain and a fragile ecological environment due to their location in the transitional zone between the Jianghan Plain and the Mufu Mountain Range. However, research gaps remain in citrus suitability evaluation for southeastern China. Therefore, this study applies GIS-AHP-fuzzy mathematics to Tongcheng County, establishing a framework for citrus land suitability evaluation and sustainable industry planning.

Materials and methods

Overview of the study area

Tongcheng County, located in Hubei Province, lies geographically between 113°36′E and 114°4′E, as well as between 29°2′N and 29°24′N (Figure 1). The county encompasses a total area of 1,131 km^2. It is positioned on the northern foothills and midsection of the Mufu Mountains, which are part of the low mountainous and hilly region in southeastern China. The topography is primarily hilly and mountainous, with mountains encircling the eastern, southern, and western sides, while the northern region remains relatively flat and open. This intricate terrain has given rise to a variety of local microclimates. The region has a northern subtropical monsoon climate with mild temperatures and abundant rainfall. Seasonal variation includes overlapping periods of precipitation and heat. The region experiences a frost-free period of approximately 302 days, with annual precipitation ranging from 1,600 to 1,900 mm and an effective accumulated temperature

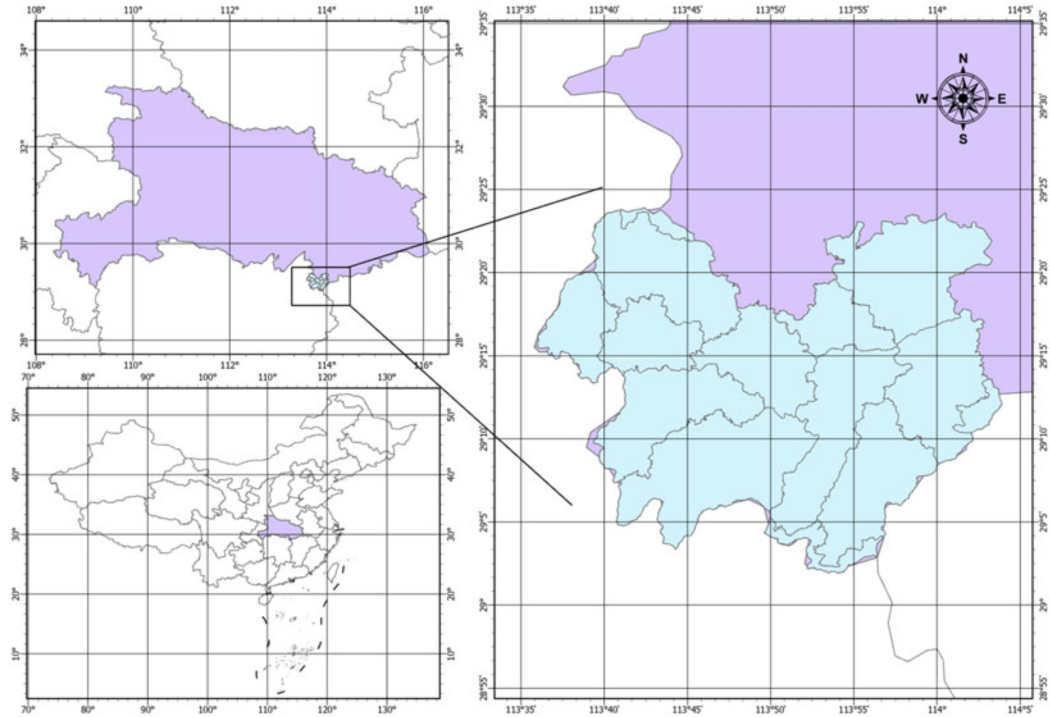

Figure 1. The location of Tongcheng County.

($\geq$10°C) of around 5,400°C. Winter frost poses a potential threat; the recent minimum recorded was –9.1°C. Seasonal drought typically occurs from July to October, which may impact fruit expansion. Influenced by Mount Mufu, the southeastern region of the county experiences daily maximum precipitation ranging from 200 to 270 mm. This substantial rainfall sustains a well-developed river network, resulting in an average annual runoff of 864×10^6 m^3 (Khan and Zaheer, 2022). Collectively, Tongcheng County's natural endowments provide favourable ecological conditions for citrus cultivation. (Opedal *et al.*, 2015).

Data sources

This study integrates multi-source data to obtain climatic, topographic, and soil information for the study area (AbdelRahman *et al.*, 2016). Climatic data (temperature, precipitation, humidity) were obtained from the 'Daily Value Dataset of Basic Meteorological Elements of National Ground Meteorological Stations in China (V3.0)'. This dataset was released by the China Meteorological Administration. It covers the period from 1961 to 2020. Meteorological station data were selected from the study area and its surrounding typical citrus planting areas. Linear interpolation and angular distance weighting methods were used. Climate raster data with a resolution of 0.25°×0.25° was generated. Indicators such as temperature, precipitation, and relative humidity were obtained. Topographic data (30 m DEM, Geospatial Data Cloud) were processed in ArcGIS 10.3 to derive evaluation metrics. Soil data were collected from 534 sampling points, including location and physicochemical properties (Figure 2). This information was cross-verified with publicly available data from the Soil Information Service Platform. Auxiliary data (administrative divisions, land use maps) were also collected to support analysis (Theobald, 2014).

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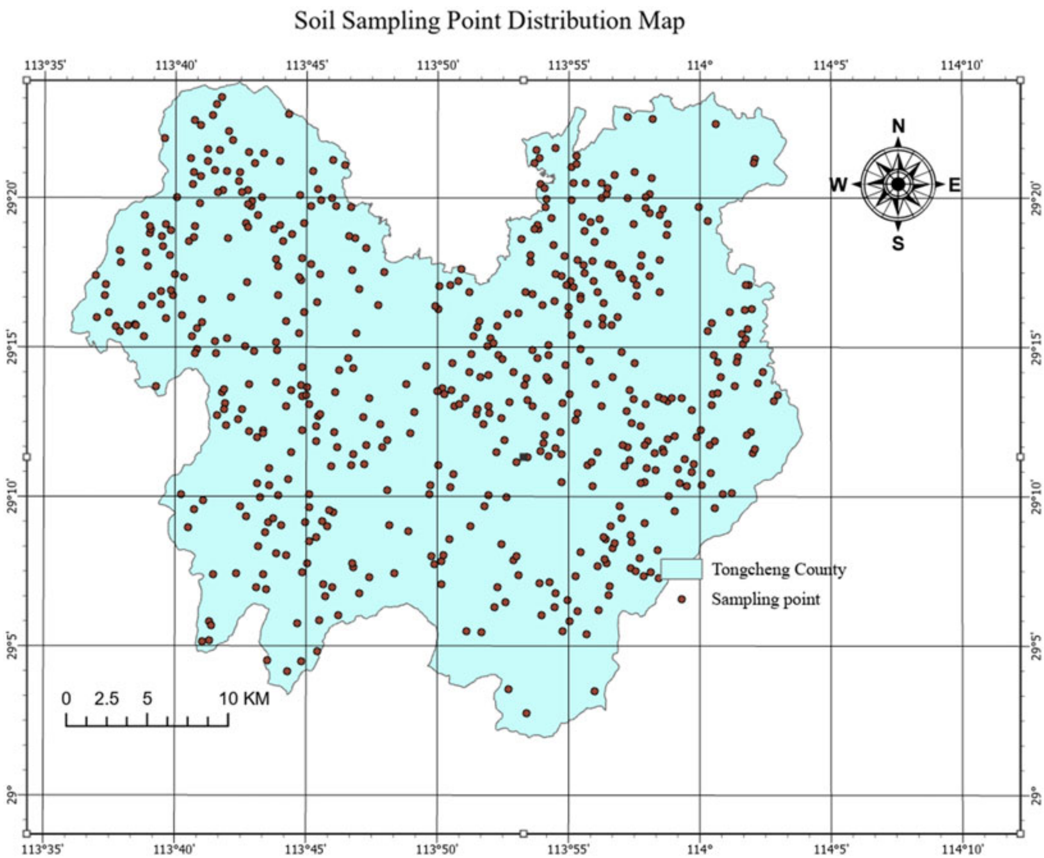

Figure 2. Soil sampling distribution map of Tongcheng County.

Delineation of evaluation units

Land evaluation units are the basic spatial units for mapping and assessment (Zonneveld, 1989). Consequently, this study utilised spatial overlay analysis. Land use, soil (1:50,000), geomorphology, and administrative maps were overlaid in GIS to define evaluation units. To ensure the accuracy of the evaluation results, plots that share the same soil type, land use type, and administrative classification are defined as a single evaluation unit. Small patches were merged and fragmented areas removed to preserve consistency in topography and soil type (Xv *et al.*, 2025).

Construction of the land suitability evaluation model for citrus cultivation selection of evaluation factors

Evaluation factors were selected for stability, dominance, and significance rather than comprehensiveness. The process should adhere strictly to the principles of stability, dominance, and comprehensiveness in order to identify stable and dominant factors (Tan *et al.*, 2020). Field investigations, literature reviews, and expert consultations informed PCA to identify suitable indicators. Climate serves as a fundamental determinant in the development of citrus agriculture. Changes in precipitation, light, and temperature will directly disrupt the previously stable equilibrium between citrus crops and their climatic conditions, resulting in shifts in the regions suitable for cultivation (Orhan, 2021). Soil properties (pH, organic matter, trace elements) regulate

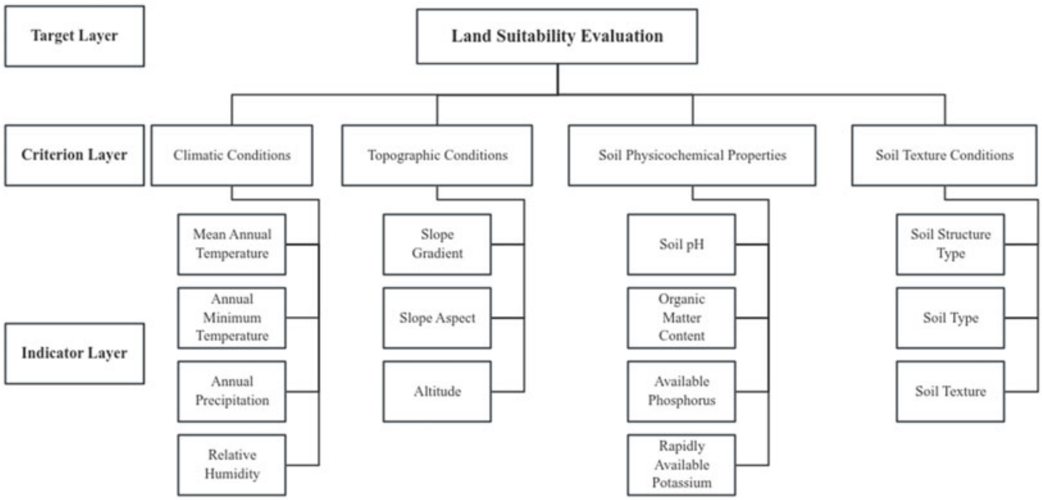

Figure 3. Map of the land suitability evaluation system for citrus cultivation in Tongcheng County.

the microenvironment, ion exchange, and yield stability (Roussos *et al.*, 2019). Topographic factors (slope, aspect, altitude) strongly influence citrus suitability (Anand *et al.*, 2022).

Establishment of the hierarchical structure

MCDA is widely used in land suitability evaluation, integrating soil, terrain, and climate criteria. It enables decision-makers to assess alternatives based on various criteria. In land suitability evaluation, the GIS-MCDA methodology utilises multiple spatial factors, including soil, terrain, and climate, as evaluation criteria to conduct a thorough scoring of each land parcel within the study area (Chandrakala *et al.*, 2022).

Among the various MCDA techniques, the AHP stands out for its prominence. AHP decomposes complex decisions into hierarchical objectives, criteria, and alternatives, integrating qualitative and quantitative analysis. This approach facilitates a comprehensive evaluation by integrating qualitative judgments with quantitative calculations (Taherdoost, 2017). Thus, in this study, the assessment system can be categorised into three hierarchical levels: the target layer being citrus land suitability, and the criterion layer comprising climate, topography, soil physicochemical properties, and soil quality conditions. The indicator layer includes 14 factors (e.g., annual precipitation, minimum temperature). Consequently, an evaluation system for citrus cultivation was developed based on these indicators (Figure 3).

A crucial aspect of the AHP is the consistency check, which verifies the absence of substantial logical contradictions in the judgments offered by experts. This is achieved through the calculation of the Consistency Ratio (CR), thereby ensuring the scientific validity and reliability of the assigned weights (Shaloo *et al.*, 2022). In this study, the CR was calculated to validate expert judgments; all CR < 0.1, confirming reliability (Lukinskiy *et al.*, 2021). The detailed hierarchical structure of the evaluation system, along with its corresponding weight values, is presented in Table 1.

Fuzzy set modelling

AHP relies on expert scoring, introducing subjectivity. Fuzzy logic reduces uncertainty by modelling membership degrees. Resulting in evaluation outcomes that are smoother and more aligned with real-world conditions. The primary advantage of this method is its incorporation of

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Table 1. Land suitability evaluation indicators and their weightings for citrus cultivation in Tongcheng County

Target layer	Criterion layer	Indicator layer	Weight
Land suitability evaluation for citrus cultivation in Tongcheng County	Climatic conditions	Mean annual temperature	0.0528
		Annual minimum temperature	0.0528
		Annual precipitation	0.0414
		Relative humidity	0.0414
	Topographic conditions	Slope gradient	0.0388
		Slope aspect	0.0389
		Altitude	0.1179
	Soil physicochemical properties	Soil pH	0.1281
		Organic matter content	0.1492
		Available phosphorus	0.0682
		Rapidly available potassium	0.0682
	Soil texture conditions	Soil structure type	0.0407
		Soil type	0.1110
		Soil texture	0.0505

the central concept of 'membership degree,' which offers a foundational mathematical framework for managing uncertainty and nonlinear relationships within systems. This framework allows for the precise characterisation and simulation of complex real-world scenarios (Seyedmohammadi *et al*., 2019).

Membership degree (0–1) quantifies how indicator values belong to suitability grades, defined by membership functions (Singh and Huang, 2023).

Membership functions used include parabolic, S-shaped, inverted S-shaped, and scatter-type (AbdelRahman *et al*., 2018; Ahamed *et al*., 2000).

When the membership function is a parabolic function, its expression is:

$$\mu(x) = \begin{cases} 1.0 & b \le x \le c \\ \frac{x-a}{b-a} \times 0.9 + 0.1 & a < x < b \\ \frac{d-x}{d-c} \times 0.9 + 0.1 & c < x < d \\ 0.1 & x \le a, x \ge d \end{cases} \tag{1}$$

When the membership function is an S-shaped function, its expression is:

$$\mu(x) = \begin{cases} 1.0 & x \ge d \\ \frac{x-a}{d-a} \times 0.9 + 0.1 & a \le x < d \\ 0.1 & x < a \end{cases} \tag{2}$$

S-shaped functions model gradual suitability increases, while inverted S-shaped functions represent gradual decreases. When the membership function is an inverted S-shaped function, its expression is:

$$\mu(x) = \begin{cases} 1.0 & x < a \\ \frac{d-x}{d-a} \times 0.9 + 0.1 & a \le x < d \\ 0.1 & x > d \end{cases} \tag{3}$$

When the membership function is a scatter-type function, its expression is:

$$\mu(x) = \begin{cases} N_1, x = \text{type } 1 \\ N_2, x = \text{type } 2 \\ \quad \cdots \cdots \\ N_n, x = type\ n \end{cases} \tag{4}$$

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Determination of evaluation indicator membership degrees

Grounded in fuzzy mathematics and informed by literature and expert consultations, the study integrated the growth characteristics of citrus with the climatic, topographic, and soil physicochemical conditions of Tongcheng County. The Delphi method was used to determine membership degrees, which were then fitted to functional relationships. Indicator thresholds (lower, optimal lower, optimal upper, upper) correspond to parabolic function inflection points a, b, c, and d (Zhang, 2022). Table 2 presents the detailed membership functions. Parabolic membership functions were employed to depict the relationships between organic matter content, pH, altitude, and citrus production potential. Parabolic functions modelled organic matter, pH, and altitude. S-shaped functions modelled temperature, precipitation, phosphorus, and potassium. Inverted S-shaped functions modelled humidity and slope gradient. Scatter-type functions modelled slope aspect, soil structure, type, and texture, with membership degrees assigned by expert judgment (Burrough *et al.*, 1992). Details are provided in Table 3.

Calculation of suitability evaluation scores

This study followed the UN (1976) 'Framework for Land Evaluation' (AbdelRahman *et al.*, 2018). By employing the weighted overlay tool within ArcGIS 10.3 and incorporating the actual land conditions and soil nutrient variation grades of the citrus cultivation area in Tongcheng County, a land suitability evaluation distribution map was produced. Weighted overlay in GIS combines multiple spatial layers with assigned weights to generate suitability maps (Basharat *et al.*, 2016).

The Citrus Appropriateness Index (CAI) utilises a calculation method similar to the linear additive combination model, with its mathematical expression articulated as follows:

$$CAI = \sum_{i=1}^{n} \omega_i \cdot \mu_i \tag{5}$$

Where CAI represents the Citrus Appropriateness Index; where ω_i is the weight and μ_i the membership degree of indicator i. Both range from 0–1, so CAI values also range from 0 (unsuitable) to 1 (ideal).

Grade classification

Suitability classes were defined based on statistical distribution, current land use, and the principle of maximising between-class heterogeneity while minimising within-class homogeneity (Mistri and Sengupta, 2020). Based on the current citrus cultivation conditions in Tongcheng County, threshold values of 0.75 and 0.55 for the CAI were established to categorise land suitability for citrus cultivation into three distinct grades: CAI ≥ 0.75 = Optimal Zone; 0.55–0.75 = Suitable Zone; CAI ≤ 0.55 = Unsuitable Zone. It is important to emphasise that the notion of 'land suitability' in this research is not a strict binary assessment but rather a nuanced concept that embodies both relative and fuzzy characteristics (Wang and Nanehkaran, 2024). Unsuitable' indicates relatively low suitability compared to optimal zones, but does not mean land is entirely unfit for citrus cultivation.

Results

Statistical results of land suitability evaluation for citrus cultivation in Tongcheng County

Soil, site, and climate membership maps were overlaid in ArcGIS 10.3 to generate the suitability map (Figure 4). Statistical analysis of data from each zone produced a table summarising the land suitability evaluation results for citrus cultivation in Tongcheng County (details provided in Table 4). Optimal Zone: 75.8%, Suitable Zone: 19.6%, Unsuitable Zone: 4.6%. Optimal zones

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Table 2. Membership function types and their inflection point values for selected indicators

Indicator	Function type	Function formula	X lower bound	Optimal lower bound	Optimal upper bound	X upper bound
Mean annual temperature	S-shaped	$\mu(x) = \begin{cases} 1.0 & x \geq 19 \\ \frac{x-14}{5} \times 0.9 + 0.1 & 14 \leq x > 19 \\ 0.1 & x < 14 \end{cases}$	14	–	–	19
Annual minimum temperature	S-shaped	$\mu(x) = \begin{cases} 1.0 & x \geq -4 \\ \frac{x+10}{5} \times 0.9 + 0.1 & -10 \leq x < -4 \\ 0.1 & x < -10 \end{cases}$	−10	–	–	−4
Annual precipitation	S-shaped	$\mu(x) = \begin{cases} 1.0 & x \geq 1900 \\ \frac{x-1500}{400} \times 0.9 + 0.1 & 1500 \leq x < 1900 \\ 0.1 & x < 1500 \end{cases}$	1,500	–	–	1,900
Relative humidity	Inverted S-shaped	$\mu(x) = \begin{cases} 1.0 & x < 67 \\ \frac{76-x}{9} \times 0.9 + 0.1 & 67 \leq x < d \\ 0.1 & x > 76 \end{cases}$	67	–	–	76
Slope gradient	Inverted S-shaped	$\mu(x) = \begin{cases} 1.0 & x < 6 \\ \frac{25-x}{19} \times 0.9 + 0.1 & 6 \leq x < 25 \\ 0.1 & x < 25 \end{cases}$	6	–	–	25
Altitude	Parabolic	$\mu(x) = \begin{cases} 1.0 & 150 \leq x \leq 800 \\ \frac{x-73}{67} \times 0.9 + 0.1 & 73 < x < 150 \\ \frac{150-x}{81} \times 0.9 + 0.1 & 800 < x < 881 \\ 0.1 & x \leq 73, x \geq 881 \end{cases}$	73	150	800	881
Soil pH	Parabolic	$\mu(x) = \begin{cases} 1.0 & 6.5 \leq x \leq 7.0 \\ \frac{x-4.1}{2.4} \times 0.9 + 0.1 & 4.1 < x < 7.0 \\ \frac{8.2-x}{1.2} \times 0.9 + 0.1 & 7.0 < x < 8.2 \\ 0.1 & x \leq 4.1, x \geq 8.2 \end{cases}$	4.1	6.5	7.0	8.2
Organic matter content	Parabolic	$\mu(x) = \begin{cases} 1.0 & 15 \leq x \leq 35 \\ \frac{x-2}{13} \times 0.9 + 0.1 & 2 < x < 15 \\ \frac{55-x}{20} \times 0.9 + 0.1 & 35 < x55 \\ 0.1 & x \leq 2, x \geq 55 \end{cases}$	2	15	35	55
Available phosphorus	S-shaped	$\mu(x) = \begin{cases} 1.0 & x \geq 77 \\ \frac{x-77}{76.9} \times 0.9 + 0.1 & 0.1 \leq x < 77 \\ 0.1 & x < 0.1 \end{cases}$	0.1	–	–	77
Rapidly available potassium	S-shaped	$\mu(x) = \begin{cases} 1.0 & x \geq 245 \\ \frac{x-10}{235} \times 0.9 + 0.1 & 10 \leq x < 245 \\ 0.1 & x > 10 \end{cases}$	10	–	–	245

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Table 3. Membership degrees of scatter-type indicators

Slope aspect		Structure type		Soil type		Soil texture	
Membership degree	Description	Membership degree	Description	Membership degree	Description	Membership degree	Description
1.0	Flat	1	Loose over compact	0.85	Sandy loam	0.95	Red soil
0.5	East	0.9	Spongy	0.70	Clay loam	0.65	Paddy soil
0.5	West	0.75	Compact	0.95	Loam	0.8	Yellow-brown soil
1.0	South	0.65	Interlayered	0.75	Clay	0.55	Limestone soil
0.3	North	0.45	Compact over loose	0.60	Sand	0.60	Fluvo-aquic soil
0.4	Northeast	0.35	Loose	–	–	–	–
0.8	Southeast	0.3	Thin-layered	–	–	–	–
0.2	Northwest	–	–	–	–	–	–
0.7	Southwest	–	–	–	–	–	–

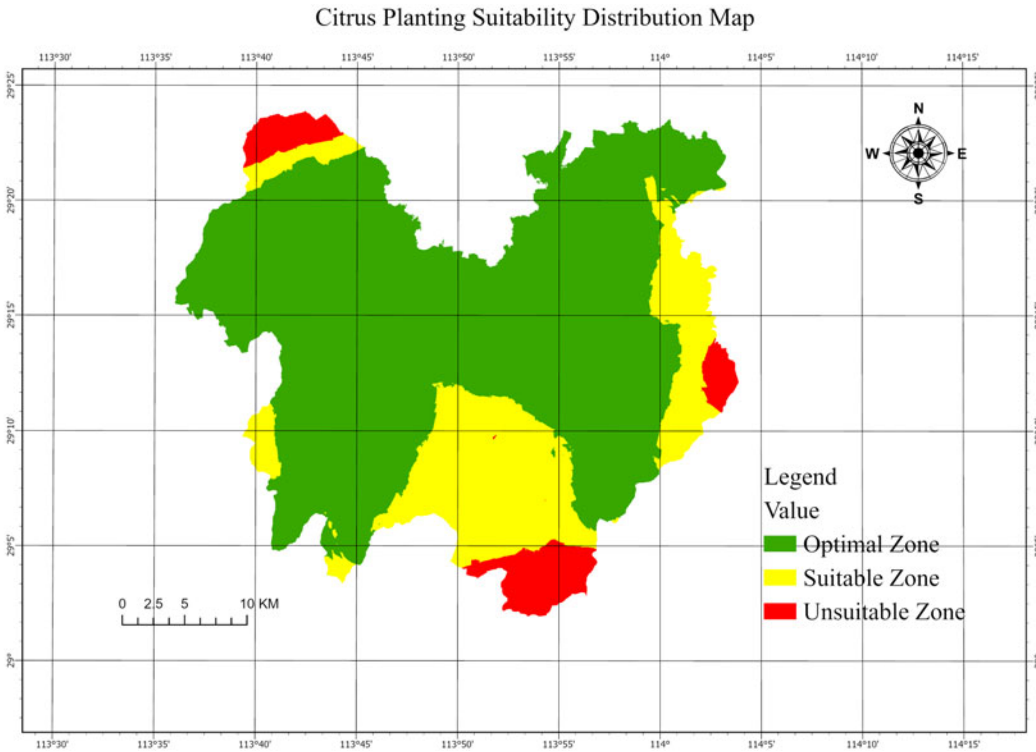

Figure 4. Distribution map of citrus land suitability evaluation in Tongcheng County.

dominate central and western regions. Suitable zones form belts in the northeast, northwest, and south. Unsuitable zones occur mainly in high-altitude southern mountains.

Validation of the suitability evaluation results for citrus-producing areas in Tongcheng County

Field investigations of yield and quality confirmed strong consistency with evaluation results, validating the model, thereby effectively corroborating the suitability evaluation conclusions of this study.

Evaluation of indicator factor suitability

Climatic factors averaged 0.8; precipitation was most influential (0.98). This phenomenon arises from the precipitation characteristics of Tongcheng County, which are particularly conducive to citrus cultivation. The county's annual average precipitation is 1,556 mm, 1,267 mm occurring between April and October. 81% of rainfall occurs from April-October, coinciding with citrus growth stages and meeting water needs. Annual minimum temperature (0.73) was the main limiting factor due to frost susceptibility during overwintering. During the overwintering period, the risk of extreme low temperatures in key growing regions poses a significant threat to the trees. Topographic factors averaged 0.7; altitude was most influential (0.83). This prominence can be attributed to the heightened sensitivity of citrus root systems to temperature fluctuations. Mountain climates with diurnal variation, sunlight, and drainage create suitable altitudinal zones, and promote high-quality and abundant yields of various fruit trees. Slope aspect averaged 0.55, limited by the predominance of north-facing slopes, reducing solar radiation, which restricts the influence of solar radiation on the cultivation areas. In contrast to studies conducted in the citrus

Table 4. Statistical table of land suitability evaluation results for citrus cultivation in Tongcheng County

Land suitability grade	Area (km^2)	Percentage of total area
Optimal zone (CAI $\geq$ 0.75)	857.3145	75.78
Suitable zone(0.55 $\leq$ CAI $\leq$ 0.75)	221.827656	19.62
Unsuitable zone (CAI $\leq$ 0.55)	52.087161	4.60
Total	1131.229317	100

cultivation areas of the Middle-Lower Yangtze Plain, this research reveals that topographic factors play a significantly more critical role in the assessment of the Tongcheng mountainous region. Unlike plain regions where drainage and groundwater dominate, mountainous Tongcheng is constrained by slope erosion and aspect-related thermal conditions.

Soil properties averaged 0.6; organic matter contributed most (0.8). This phenomenon primarily results from the generally high soil organic matter content in the study area, where the majority of sampling points exhibit values ≥15 g/kg. This level of organic matter sufficiently fulfils the nutrient supply requirements necessary for citrus growth. In contrast, available phosphorus was limiting (0.5), with average content 15.3 mg/g, insufficient for citrus needs, thereby limiting the citrus production potential in this region to some degree (Saraswat *et al.*, 2023).

Soil textures included loam (0.95), sandy loam (0.85), clay (0.75), clay loam (0.70), and sandy (0.60). Loam (0.95) was most suitable, combining permeability, aeration, and nutrient retention. It is predominantly found in the central and western areas of the region. Sandy loam (0.85) supports root development and early growth. This soil type is widely distributed throughout the region. Clay loam (0.70) and clay (0.75) retain water/nutrients despite poorer drainage. In contrast, sandy soil (0.60) was least suitable due to poor water/nutrient retention. The distribution is primarily concentrated in the mountainous regions of the south. Overall soil texture averaged 0.77, indicating generally suitable conditions for citrus (AbdelRahman *et al.*, 2022).

Discussion

The climate data utilised in this study covers the years 1961 to 2020. It reflects the average conditions for that period. Throughout this timeframe, the study area exhibited a pronounced warming trend. This trend was accompanied by increased precipitation variability. Duan *et al.* (2025) found that from 1995 to 2014, the intensity of extreme maximum temperature events in central China rose. The rate of increase was 0.19°C per decade. High-value areas were predominantly located in the eastern Hubei region. This suggests that the classification boundaries for citrus cultivation suitability are not static. Future research should incorporate climate scenario data. It should also perform dynamic evaluations.

In summary, the optimal zones (300–500 m elevation, gentle sunny slopes, deep sandy loams, organic matter 29.4 g/kg, pH 6.6) provide favourable drainage and reduced frost risk. Within Tongcheng County, these areas constitute the largest suitability class and are characterised by a widespread, concentrated distribution, particularly in the western and central regions (Dobos *et al.*, 2025). Thus, this area not only functions as a crucial foundation for current premium citrus production but also represents the central region for the future scaled and intensive development of the industry. Enhancing its leading role requires a multi-pronged approach: introducing market-adapted superior varieties (De Roest *et al.*, 2018). Developing standardised ecological orchards, promoting green technologies, and adopting intelligent management to improve fruit quality and ensure sustainable production (Miglietta *et al.*, 2019). These measures will strengthen Tongcheng's citrus industry, enhance agglomeration effects, and increase competitiveness (Varma *et al.*, 2024). Consequently, they will elevate the overall competitiveness of the Tongcheng citrus industry to a higher level (Dong *et al.*, 2024).

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The optimal regions for citrus cultivation are primarily located in the Eastern and Southern regions. Eastern and southern regions have higher altitudes and steeper slopes, increasing erosion risk. Hilly terrain blocks cold air, creating favourable overwintering conditions. Soils (organic matter 25.9 g/kg, pH 6.4) are generally suitable (Ngoi *et al.*, 2021). Some parcels deviate from optimal pH, limiting growth (Neguşier *et al.*, 2024). Overall, this region has a robust production base, yet precise improvements are needed to optimise site conditions and address local soil variations, thereby unlocking its full potential (Yang *et al.*, 2022). Targeted soil optimisation and investment can enhance productivity, economic benefits, and competitiveness (Getahun *et al.*, 2024).

Unsuitable zones (south, east, northwest) have high altitudes, rugged terrain, severe erosion, and limited mechanisation (Li *et al.*, 2021). Moreover, this zone features a generally favourable environment, but North-south slopes increase frost risk; soils (OM 13.2 g/kg, pH 6.1) are sandy with poor retention (Agbede *et al.*, 2022). *T* Consequently, Future use should prioritise ecological conservation (AbdelRahman and Arafat, 2020), replacing citrus with indigenous tree species that conserve soil and water (Başkent and Başkent, 2025; Nyagumbo *et al.*, 2024;).

AHP-weighted overlay, a prevalent method in contemporary GIS-MCDA, fundamentally remains a linear combination. It inherently presumes independence among the different factors, and the final score generated is a definitive numerical value. Classic AHP-GIS offers binary results, while fuzzy mathematics provides a continuous 'suitability surface' (Tercan and Dereli, 2020). The primary innovation of this study is the application of fuzzy mathematics theory to land suitability evaluation. This approach resembles the use of a greyscale camera, which captures the nuanced spectrum of shades between white and black, resulting in a suitability map that represents a continuous 'suitability surface.' The evaluation outcomes offer a scientific assessment for crop cultivation in the ecologically sensitive red soil hilly region of southeastern China.

Secondly, within the classic AHP-GIS methodological framework (AbdelRahman *et al.*, 2025), AHP relies heavily on expert scoring, introducing subjectivity and limiting applicability. This approach often fails to sufficiently account for the fuzziness and uncertainty inherent in evaluation criteria, resulting in findings that frequently possess limited applicability for crop cultivation in similar regions (Felipe *et al.*, 2024). To address this issue, this study incorporated fuzzy mathematics theory into the evaluation methodology based on field investigations. Fuzzy mathematics defines membership functions, enabling smoother transitions between grades and more realistic outcomes (Seyedmohammadi and Navidi, 2022). Incorporating fuzzy mathematics, this study established an AHP-GIS framework for citrus land suitability evaluation in the ecologically vulnerable red soil hilly region of southeastern China. This fuzzy-AHP-GIS framework aligns with actual production conditions and can be applied to other crops in similar mountainous regions.

The primary contribution of the GIS-AHP fuzzy comprehensive evaluation framework is that it provides a general methodology for assessing agricultural land suitability, thereby facilitating the analysis and optimisation of land use planning (Zakarya *et al.*, 2021). This method is transferable, but its effectiveness depends on close integration with local conditions. Specifically, the framework comprises two parts: transferable core processes and localised components requiring recalibration.

Transferable components include: (1) the multi-criteria hierarchical structure; (2) the AHP weight derivation procedure; (3) the selection of fuzzy membership function types; and (4) the GIS-based weighted overlay workflow.

Components requiring localisation include: (1) the evaluation criteria themselves, which must reflect local environmental and agricultural characteristics; (2) the definition and thresholds of fuzzy membership functions, tailored to local crop physiology and agronomic practices; and (3) the relative weights of criteria, which should be re-established through consultation with regional experts.

For example, Molla (2024) used fuzzy-AHP and GIS to assess land suitability for rice and green gram in India's Sundarban region, identifying 19 criteria via expert consultation. Similarly,

https://doi.org/10.1017/S0014479726100313 Published online by Cambridge University Press

Abuzaid *et al.* (2025) applied AHP weighting and fuzzy membership functions to evaluate wheat, broad beans, and corn in Egypt's Nile Delta, integrating meteorological data, a DEM, and 70 soil profiles.

This framework provides a structured template. Effective application requires integrating local agricultural conditions and expert knowledge into each component, ensuring scientifically robust and practically valuable assessments for agricultural decision-making.

Conclusions

This study presents a comprehensive framework for citrus land suitability assessment, addressing single-source data limitations by integrating GIS, AHP, and fuzzy mathematics. This research quantitatively evaluates land suitability for citrus cultivation in Tongcheng County. Suitability evaluation in Tongcheng County is essential for sustainable citrus cultivation, given local soil, site, and climate conditions. The results show: Optimal Zone: 75.8% (857 km^2); Suitable Zone: 19.6% (222 km^2); and Unsuitable Zone: 4.6% (52 km^2). Findings guide land-use optimisation and yield improvement, highlighting the need for further research in ecologically vulnerable red soil hilly regions in southeastern China. The framework can also quantify production potential and limiting factors for other erosion-affected crops. Future research should refine indicators, optimise methods, and strengthen spatial analysis to improve reliability. Further studies should link suitability evaluation with actual production outcomes to provide a stronger scientific basis for decision-making. This exploration would provide a scientific foundation for decision-making in citrus production and enhance the effectiveness of citrus cultivation practices.

Author contributions. Yu Liu: Conceptualisation; data curation; investigation; methodology; software; validation; writing-original draft; writing-review and editing. Qiang Jin: Conceptualisation; formal analysis; funding acquisition; investigation; project administration; resources; software; writing-original draft; writing-review and editing. Xinchuang Xu: Conceptualisation; formal analysis; investigation; methodology; resources; visualisation; writing-review and editing. Ruikai Chen: Data curation; formal analysis; funding acquisition; methodology; resources; software; supervision; writing-review and editing. Peng Guo: Data curation; formal analysis; funding acquisition; methodology; project administration; resources; software; supervision; validation; visualisation; writing-review and editing. Chao Yang: Conceptualisation; investigation; methodology; resources; supervision; writing-original draft; writing-review and editing.

Funding statement. This research was financially supported by the Youth Program of Natural Science Foundation of Hubei Province (2024AFB323); Hubei University of Science and Technology Doctoral Start-up Fund Project (BK202313).

Competing interests. The authors declare that they have no known competing economic interests or personal relationships that could influence the work presented in this article.

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Cite this article: Liu Y, Jin Q, Xu X, Chen R, Guo P, and Yang C (2026). Land suitability evaluation for citrus cultivation in southeastern Hubei, China, based on integrated AHP-GIS and fuzzy mathematical methods. *Experimental Agriculture*. https://doi.org/10.1017/S0014479726100313