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Unveiling the mechanism of diachronic changes and regional characteristics differences in the built environment of traditional villages from the perspective of color data: evidence from Macheng City, China

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Abstract

Traditional villages hold a vital place in Chinese vernacular built heritage continuation with their colors being a significant constituent of the built environment. While digital technology has advanced our understanding of built environment, current research pays little attention on how color influences the environment, often overlooking temporal changes and regional differences, especially neglects color protection measures. This study establishes an diachronic image dataset using national traditional villages in Macheng City, Hubei Province. By using of K-Means and CIEDE2000 algorithms, we analyze color characteristics differences among 4 regions in Macheng City in 2022. And, we select five year's diachronic image data of Dongyuan Village (2017–2022) to elucidate the color changes mechanisms. The results show that: (1) Elements influenced by the government, construction techniques dissemination, and environmental factors exhibit regional similarity, while the color of wall differs significantly. Specifically, K-Means values for northern and eastern wall elements indicate light brown tones [RGB: (159, 151, 136), (163, 159, 147)], whereas southwestern and central wall elements exhibit distinct colors, including grayish brown [RGB: (132, 127, 119)] and light yellow [RGB: (190, 182, 161)], respectively. (2) Dongyuan Village underwent color corrections in accordance with government policies, resulting in a shift from blue [RGB: (138, 154, 213)] to yellow [RGB: (223, 206, 196)] for the walls and a gradual unification of road colors into light gray [RGB: (239, 238, 243)]. This initiative led to increased consistency with government guidelines, and the color data stabilized with minimal changes in the surrounding environment. This study enhances our comprehension of traditional village color and regional characteristics changes, contributing to effective measures for the preservation of these culturally significant built heritage.

Keywords Color data, Traditional village, Color changes mechanism, Regional characteristics differences, Quantification analysis

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Introduction

Traditional villages are a vital component of cultural heritage, embodying historical, cultural, and technical values [1, 2]. Preserving and perpetuating the built environment of traditional villages is crucial for achieving sustainability in architectural cultural heritage within the context of contemporary rural development [3, 4].

In traditional villages, the distinctive built environment naturally arises from the spontaneous interaction of various elements. Notably, the primary visual characteristics of this kind of built environment revolve around color and its unique texture [5–7]. Among which, color plays a pivotal role, influencing the traditional built environment at multiple levels, from the built environment feature to forming visual perceptions and embodying intrinsic values [8–10]. While researchers have developed perceptual knowledge of color composition in traditional villages' built environments, quantitative color analysis remains limited, calling for future study [11–13].

With advancements in image processing technology, this study focus has shifted toward quantitative color analysis based on color data, representing characteristic information obtained through image acquisition and extraction techniques [14–17]. This approach allows for a more scientific and objective understanding of color's role in the traditional built environment, providing precise guidance suggestions [18–20]. This approach prioritizes consistency in the image acquisition process, including factors such as lighting conditions, time of day and season, and photographic range. Researchers typically opt to capture images during periods of optimal local visibility while avoiding adverse weather conditions to ensure the reliability of lighting and time conditions [21–24]. Distance and angle play crucial roles in photography, with variations depending on the subject of study [25]. However, it is essential that the research subject occupies a significant portion of the main area of the image and is captured from angles and distances that maintain clarity and proportion [26].

In rural built environment studies, researchers have used color data to extract dominant colors, guiding environmental color control for regional construction [26]. Subsequently, some researchers highlighted the considerable impact of color differences on the harmony of built environments, examining how diverse building facade colors interfere with human attention [27, 28]. However, there is a gap in understanding the mechanism of built environment color change applied in traditional villages.

In regional color studies, some researchers have concentrated on addressing dominant color tendencies in urban areas and proposing corresponding color adjustments [29, 30]. Furthermore, they have conducted color comparisons among urban clusters using clustering algorithms [31]. Nevertheless, there is a notable absence of research analyzing color differences among villages in different regions. Simultaneously, these studies are lack an examination of color data characteristics related to various environmental elements in there region, hindering the ability to offer pointed color control decisions for diverse regions.

In summary, while numerous color analysis studies focus on built environments, a distinct lack of analysis addressing diachronic changes in villages and regional characteristic differences is evident. This gap is crucial for effectively supporting the conservation of color in villages' built environments. Consequently, this study advocates adopting a color data perspective to comprehend these traditional village' built environment. Through the utilization of established color data computing methods and the traditional villages in Macheng City as a case study, the research carries out the extraction of dominant colors, undertakes comparison of regional color reference intervals, and interprets analysis of diachronic color characteristics. Informed by a comprehension of the diachronic changes mechanism within traditional villages and regional characteristics, this study presents color control recommendations aimed at preserving their traditional built environment's vital aspects.

Research aims

The aim of this study is to uncover the diachronic changes mechanism and regional characteristic differences in the traditional village' built environment through the perspective of color data. The findings is to contribute a comprehensive understanding of the overall color characteristics in regions hosting traditional villages, shedding light on the causes behind color changes during their development. Furthermore, the results offer pointed recommendations for safeguarding the traditional village built environments' colors, significantly contributing to the prevention of their deterioration.

Materials and methods

In this study, we advance the sustainability of traditional village built environments through a color data perspective, offering a practical methodology (Fig. 1). The four key steps include: (a) Image acquisition through field surveys and social media, with dimension standardization to create a database; (b) Classification of main elements in traditional village built environments based on prior studies, establishing a linkage with color data; (c) Utilization of the K-Means clustering algorithm to derive clustering results characterized by cluster means; (d) Firstly,

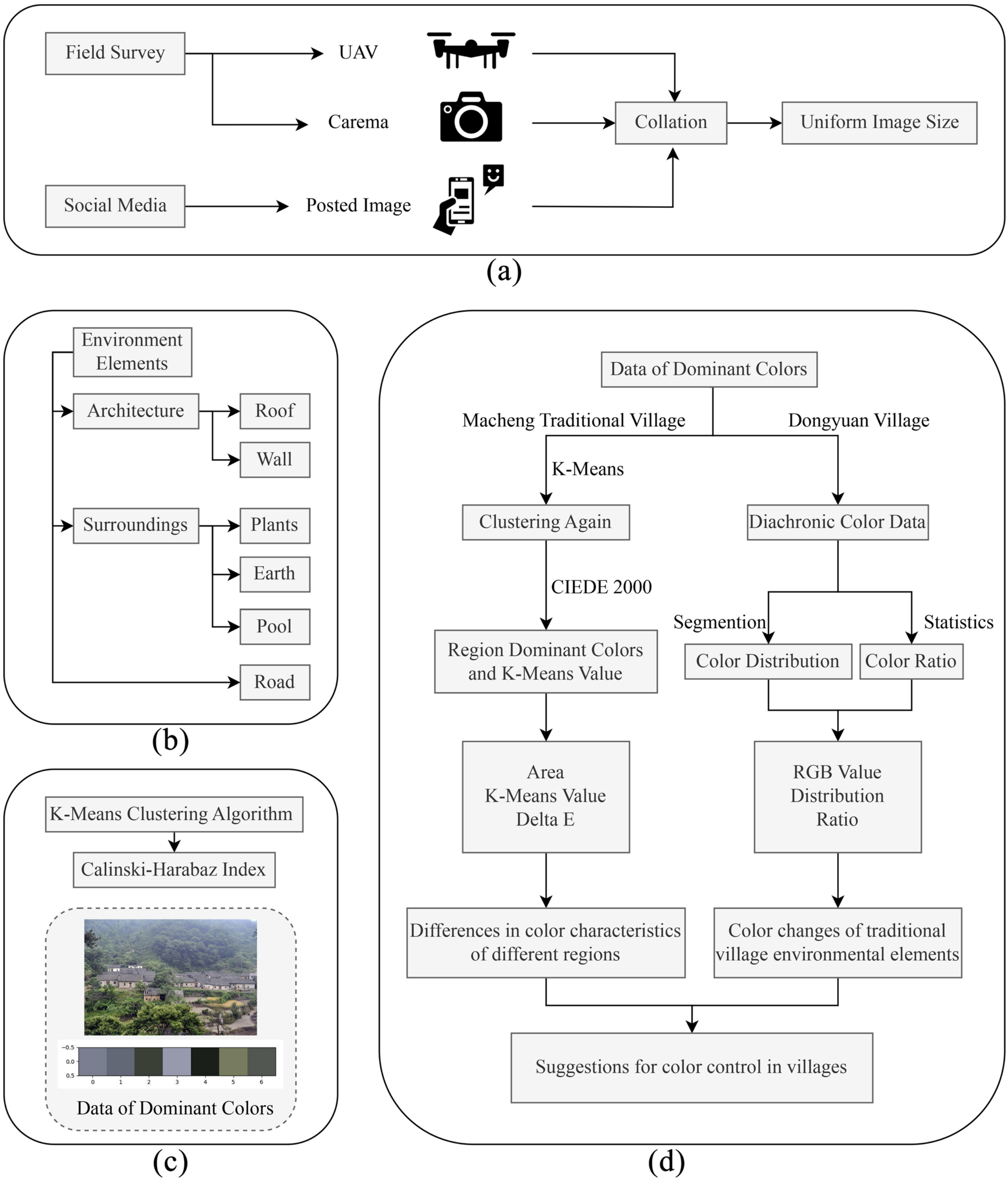

Fig. 1 Framework of traditional village color changes and regional characteristics. **a** Image acquisition and database. **b** Element classification. **c** Clustering. **d** Analysis and recommendation

application of the CIEDE2000 algorithm to calculate the color difference range between cluster mean values and true values of environmental elements, revealing color characteristic differences across regions. Secondly, analysis of the color change trend in environmental elements through the distribution and percentage of historical color data in Dongyuan Village. Finally, comprehensive analysis and explanation of results, culminating in the formulation of pertinent color control recommendations.

Case and situation

Focuses on 16 national traditional villages in Macheng City as the research subjects, distinguished from ordinary villages, offer heightened representativeness and typicality in terms of built environment color. Situated in Macheng City—a region locates in central inland of China —these villages exhibit rich cultural characteristics [32]. Functioning as a key hub for immigrant culture, Macheng has evolved into a distinctive "non-pure guest city" during cultural collisions, giving rise to various village types with unique characteristics [33, 34]. Moreover, Macheng City boasts diverse geographic environments, with the eastern and northeastern parts enveloped by high mountains, the central region featuring low hills, and the southwestern area comprising an alluvial plain. Overall, the geography showcases an elevation pattern, higher in the northeast and lower in the southwest. The national traditional villages in Macheng City are distributed as follows: four in the northern mountainous area, four in the eastern hilly region, five in the central part, and three in the southwestern alluvial plain (Fig. 2).

Data collection and processing

Color data in this study originates from images, serving as a record of the colors within traditional villages and their evolution processes. Image collection was undertaken through two avenues: (1) field surveys involving the capture of village images through photography and UAV (unmanned aerial vehicle); (2) extraction of publicly posted images from social media.

Our research team conducted multiple field surveys in traditional villages of Macheng City from 2015 to 2020, amassing a total of 10,803 images. To align with the study's focus on the overall color characteristics of traditional village built environments, data were meticulously cleaned, removing irrelevant images and resulting in a refined set of 71 images.

Supplementing the field survey data, images posted by users on social media were collected. Specifically, data from "traditional villages in Macheng" on platforms such as Sina Weibo and Xiaohongshu were crawled, covering the time span from 2016 to 2022. After stringent screening to ensure accurate location information, 46 valid photos were retained.

The 117 collected images were systematically categorized to create a dataset encompassing 16 traditional villages. Organized chronologically based on the image capture time, the dataset was further standardized, and image sizes were adjusted to 640*430 pixels (Fig. 3).

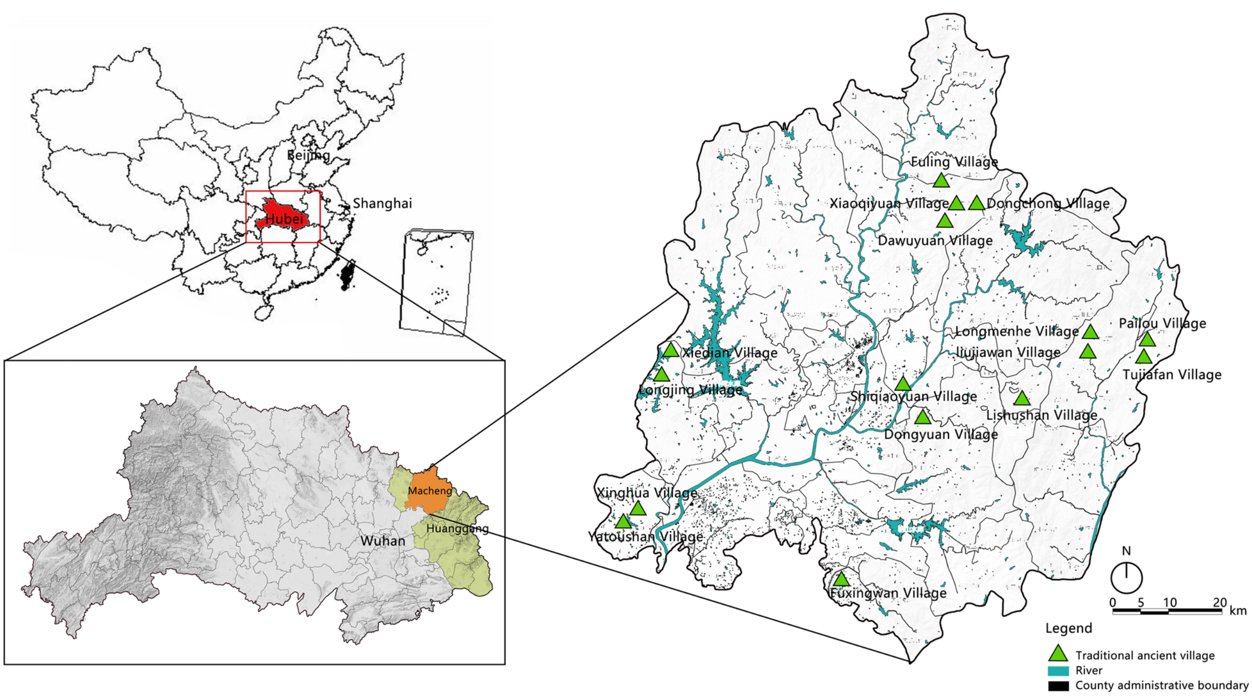

Fig. 2 Case location in China

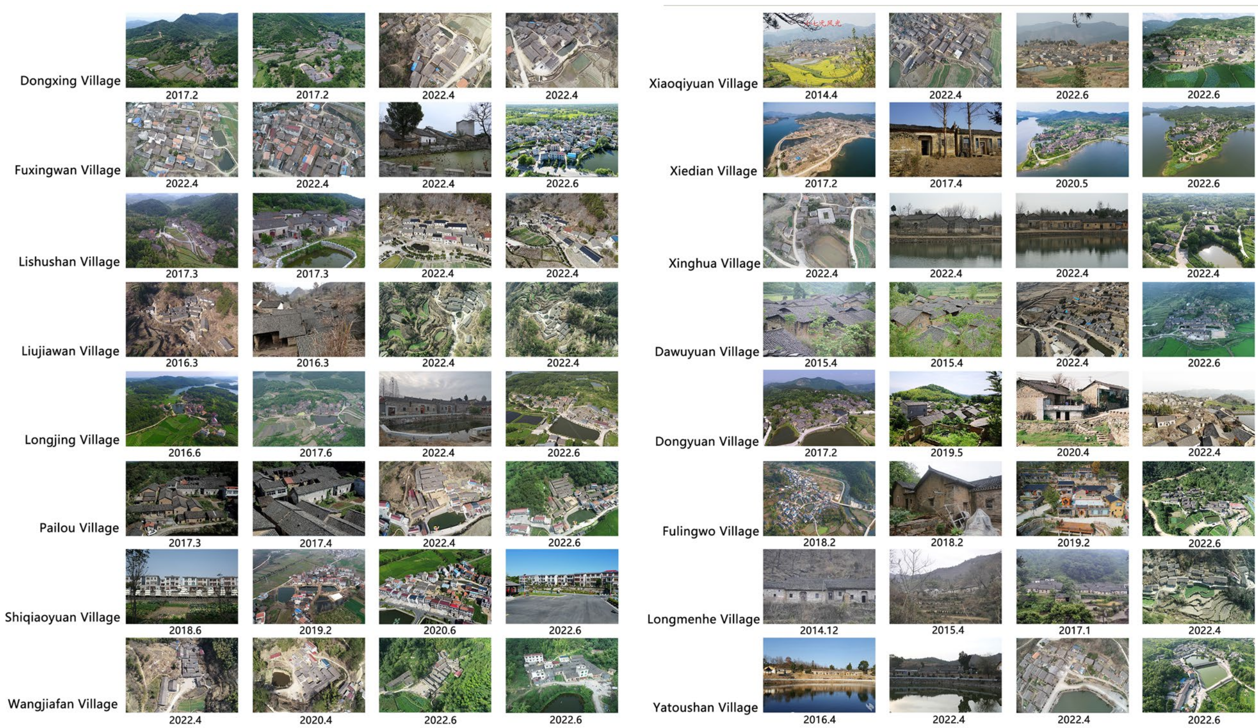

Fig. 3 Selected cases and a part of diachronic image data

In addition, several factors were carefully considered during the data acquisition and processing for this study. To ensure the quality and relevance of the imaged content, buildings were required to occupy approximately 30–50% of the image frame, with proper inclusion of surrounding environmental elements [26, 35]. This criterion guaranteed visibility of key features in the images. Moreover, climatic and weather conditions were taken into account as variable factors [36]. Image data were uniformly selected from photographs captured between Janurary and June, encompassing the spring and early summer seasons, to mitigate the adverse effects of rain, clouds, and other climatic factors. Image acquisition relied on UAV and handheld photography. To ensure optimal visual perception and color representation [24], the viewing distance was limited to 10–20 m for handheld photography, and the distance for UAV photography was limited to 100–150 m.

Methods

Classification of traditional village environmental elements

The connection between the classification of traditional village environment elements and color data still needs to be reconstructed. The village landscape includes different patterns of earth, ponds, plants and buildings, which are also the main visual elements of the built environment [37, 38]. Some researchers have pointed out that, based on the general characteristics of village buildings, the building is often a single-story or two-story house showing simple and clear walls and roofs. Therefore, the wall facade and the roof also constitute the main visual part of village buildings [26].

Some researchers analyzed the visual value of the built environment of villages and assessed the visual quality of different elements. The assessment results showed that plants and roads are the elements that rate high in the village landscape [39]. Therefore, synthesizing the previous studies, the composition of traditional village environment elements in images should include buildings, roads and surroundings. Among them, buildings consist of roofs and walls, while the surroundings include plants, earth and ponds.

K-Means clustering algorithm

Then, the K-Means clustering algorithm has been chosen for dominant color extraction. This algorithm is recognized as one of the more effective tools for addressing color clustering problems [40, 41], offering versatility for extracting different numbers and types of dominant colors, especially suitable for larger-scale image color extraction.

The K-Means algorithm operates based on Euclidean geometric distances. Initially, it randomly selects K centroids and then iteratively minimizes the loss function.

This involves fixing centroids and adjusting the category of each pixel in the sample image. Subsequently, the category of each pixel is held constant while the loss function is reduced by adjusting the position of the center point. This iterative process continues until the loss function monotonically decreases to a minimum value. At this point, the centroids and pixel categories converge simultaneously, yielding the cluster mean value (called K-Means value) and color classification for the final color data (Fig. 4).

Calinski-Harabaz index score elevation

The K-Means clustering algorithm is an unsupervised clustering learning algorithm contingent upon a predetermined number of clusters. The selection of predetermined cluster number significantly impacts the assessment of clustering results and the extraction of dominant colors. To address this, the study incorporates the CH Index (Calinski-Harabaz Index) for evaluating and determining the optimal number of clusters [42, 43].

The CH Index fundamentally represents the ratio of inter-cluster distance to intra-cluster distance, with its computation process grounded in covariance values. This CH Index aids in enhancing the precision of the clustering results and facilitates more accurate extraction of dominant colors.

$$S = \frac{\mathrm{tr}(B_k)(N-K)}{\mathrm{tr}(W_k)(K-1)} \tag{1}$$

$$\mathrm{B_k} = \sum_{q=1}^{k} n_q \left(c_q - c_e\right)\left(c_q - c_e\right)^T \tag{2}$$

$$\mathrm{W_k} = \sum_{q=1}^{k} \sum_{X \in C_q} \left(x - c_q\right)\left(x - c_q\right)^T \tag{3}$$

In the formula for the CH Index, S represents the score. The data set with N capacity is clustered into K species, where B_k is the covariance matrix between the classes, W_k is the covariance matrix of the data within the classes, c_q denotes the centroid of the class q, c_e identifies the centroid of the data set, n_q denotes the number of data in the class q, and C_q denotes the data set of the class q. Generally, a higher evaluation value of CH Index is achieved when the internal covariance of the clusters is smaller and the external covariance is larger. This

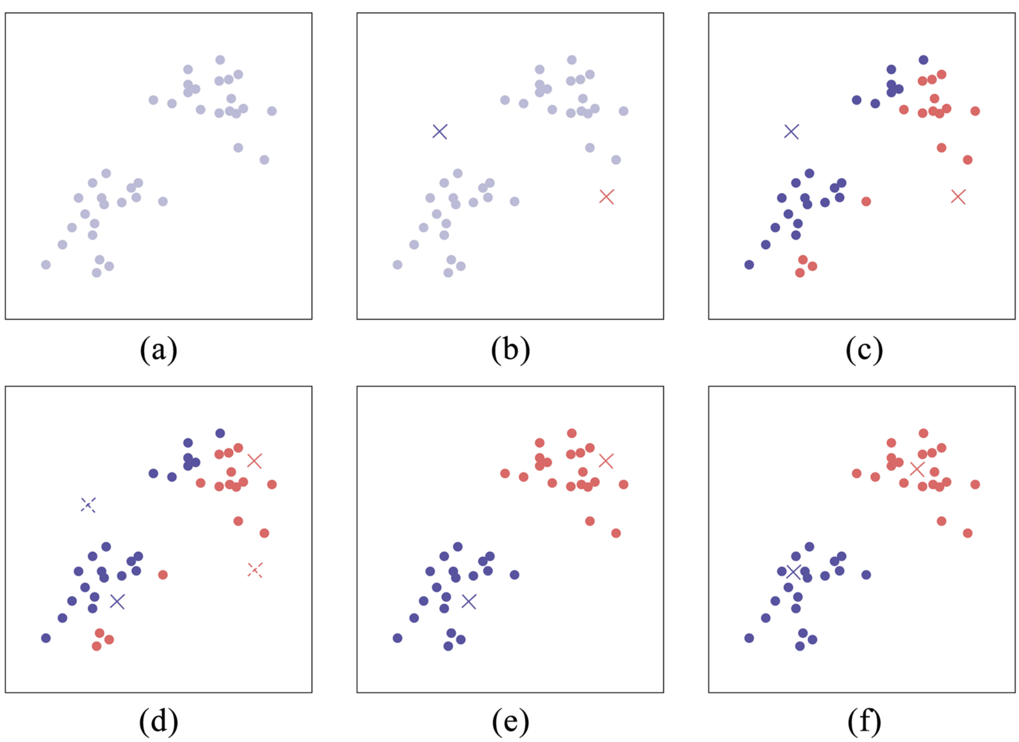

Fig. 4 K-Means algorithm principle analysis diagram. **a** Pixels to be classified. **b** Set the centroids. **c** Adjust the category of pixels. **d** Adjust the position of the centroids. **e** process iteration. **f** Convergence completed.

indicates that the number of clusters associated with the highest evaluation score is optimal.

CIEDE2000 algorithm

CIEDE2000 algorithm is commonly employed for calculating color value differences. In this study, it is utilized to quantify the range of difference between the K-Means value and the true color value [44].

CIEDE2000 operates within the Lab color space, where ΔE_{00} represents the final color difference result. Parameters ΔL^*, ΔC^*ab, and ΔH^*ab denote the differences in luminance, chromaticity, and hue, respectively. The weighting functions SL, SC, and SH are applied, and the variable RT controls the rotation angle of the ellipse. Additionally, the correction coefficients KL, KC, and KH, set to 1 under standard observation conditions [34], are crucial elements in the calculation:

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L^*}{k_L \times S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C \times S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H \times S_H}\right)^2 + R_T\left(\frac{\Delta C^*}{k_C \times S_C}\right)\left(\frac{\Delta H^*_{ab}}{k_H \times S_H}\right)} \quad (4)$$

settings to statistically identify the peak region, which represents the optimal cluster number interval for each type of images. Sample villages, along with their aerial and human views in 4 regions of Macheng City, were chosen for the calculation, and the score evaluation results are depicted in Fig. 5. The findings indicate that while the scores vary considerably across the eight classes of images, their peak regions consistently fall between cluster numbers 3 and 7. The most comprehensive inclusion of dominant colors was observed when the cluster number was set to 7. Consequently, the study sets the number of clusters to 7 for extracting the dominant color from the images.

Upon determining the optimal number of clusters, the K-Means algorithm was applied to traverse pixel points in diachronic images of traditional villages from 2015 to 2022. Clustering is performed to extract the dominant colors of the built environment.

Result

Extraction of dominant colors

The CH Index score evaluation is employed to ascertain the optimal number of clusters for various types of images, such as the number of clusters for villages in different regions and images from different viewpoints. This evaluation method calculates the CH Index score at different cluster number

Figure 6 illustrates the clustering results for 4 sample villages, including Dawuyuan Village, Yatoushan Village, Longmenhe Village, and Dongyuan Village. It encompasses traditional villages, diachronic images, and their corresponding dominant colors. Each sample village comprises multiple diachronic images, and from a single image, 7 dominant colors can be

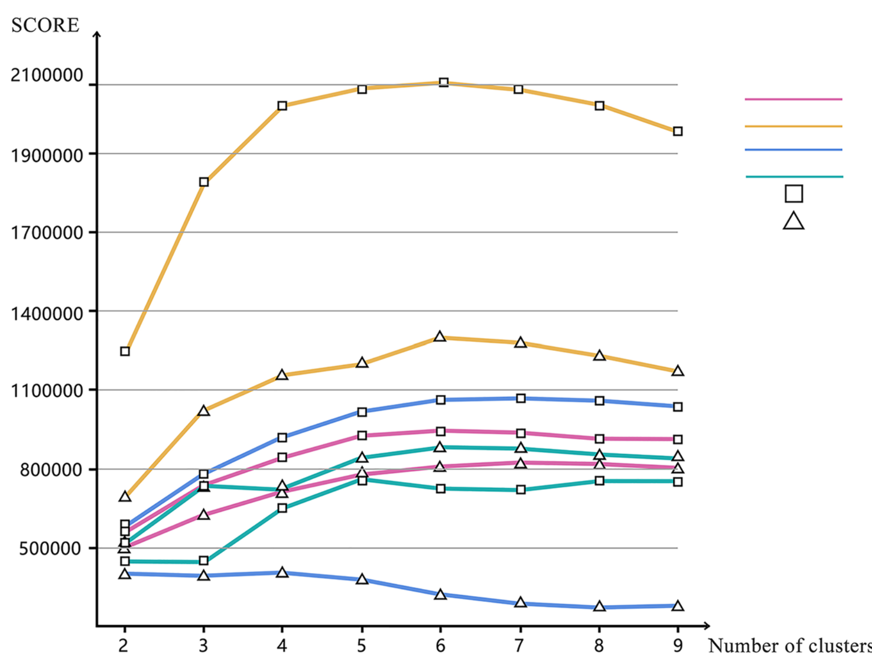

Fig. 5 The result of CH Index from 4 villages' views. The X-axis is the number of clusters. The Y-axis is the score

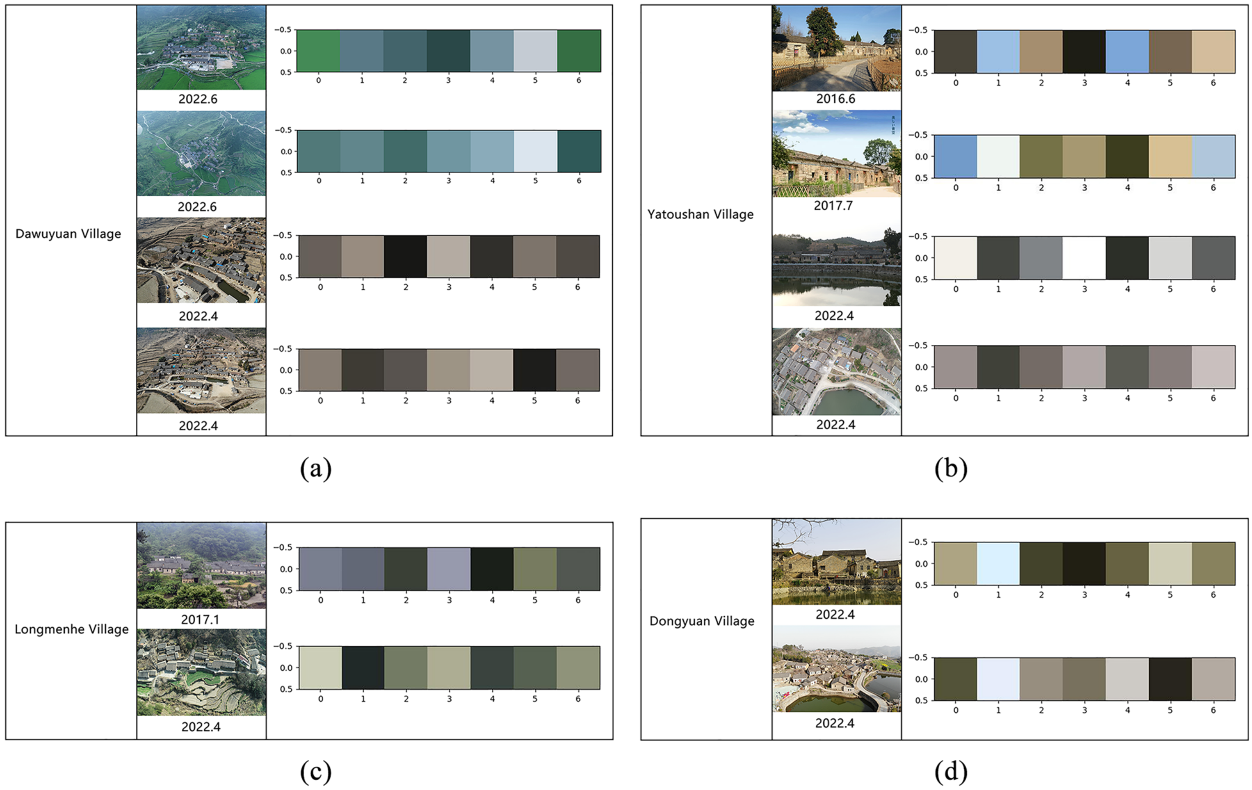

Fig. 6 The clustering results of 4 traditional villages. **a** Dawuyuan village. **b** Yatoushan village. (**c** Lonemenhe village. **d** Dongyuan village

Table 1 RGB value of the clustering results for 4 sample villages

Sample village	Diachronic images	Dominant colors (RGB value)						
		RGB 1	RGB 2	RGB 3	RGB 4	RGB 5	RGB 6	RGB 7
Dawuyuan village	Picture 1 (2022.6)	(68, 138, 86)	(89, 121, 134)	(67, 100, 107)	(42, 72, 72)	(118, 147, 161)	(196, 203, 211)	(53, 110, 67)
	Picture 2 (2022.6)	(81, 121, 121)	(97, 134, 140)	(65, 107, 105)	(112, 150, 161)	(138, 171, 186)	(219, 229, 238)	(47, 89, 88)
	Picture 3 (2022.4)	(104, 95, 90)	(152, 140, 128)	(23, 23, 21)	(180, 171, 162)	(48, 47, 43)	(125, 116, 107)	(79, 74, 68)
	Picture 4 (2022.4)	(135, 125, 115)	(62, 59, 52)	(88, 83, 79)	(157, 148, 133)	(185, 177, 166)	(29, 29, 27)	(113, 104, 99)
Yatoushan village	Picture 1 (2016.6)	(72, 68, 57)	(156, 192, 228)	(165, 142, 111)	(29, 29, 21)	(124, 166, 216)	(119, 102, 82)	(211, 188, 156)
	Picture 2 (2017.7)	(114, 155, 201)	(239, 245, 241)	(117, 114, 71)	(166, 152, 113)	(60, 61, 30)	(215, 192, 148)	(176, 198, 219)
	Picture 3 (2022.4)	(243, 240, 233)	(67, 69, 64)	(128, 132, 135)	(255, 255, 255)	(44, 47, 40)	(213, 213, 211)	(94, 96, 95)
	Picture 4 (2022.4)	(154, 144, 142)	(64, 65, 57)	(116, 107, 102)	(177, 167, 166)	(90, 91, 83)	(135, 125, 123)	(201, 191, 190)
Longmenhe village	Picture 1 (2017.1)	(121, 127, 143)	(98, 104, 118)	(58, 64, 54)	(151, 154, 173)	(26, 31, 25)	(119, 123, 96)	(82, 87, 81)
	Picture 2 (2022.4)	(204, 206, 184)	(32, 31, 40)	(115, 123, 100)	(173, 173, 147)	(58, 67, 62)	(86, 97, 81)	(143, 147, 122)
Dongyuan village	Picture 1 (2022.4)	(173, 164, 131)	(218, 241, 255)	(67, 67, 43)	(33, 31, 19)	(103, 98, 66)	(207, 205, 182)	(136, 130, 94)
	Picture 2 (2022.4)	(83, 83, 57)	(231, 237, 251)	(151, 142, 127)	(120, 113, 94)	(205, 202, 197)	(40, 37, 30)	(179, 170, 161)

extracted. These dominant colors serve as the basis for subsequent analyses of regional dominant color reference intervals and trends in color changes within typical villages. Table 1 displays the RGB values corresponding to the color clustering results of the sample villages.

Differences in color characteristics of different regions

The study focus on the built environment images of the 16 national traditional villages in Macheng City in 2022. The goal is to calculate the K-Means value and color difference ranges of dominant colors within environmental elements, facilitating a comparison of color characteristics among traditional villages in different regions. The 16 national traditional villages are the typical samples in Macheng City, which represent the color characteristics of the traditional villages in their regions.

Given that the Macheng City government implemented measures to eliminate elements interfering with the built environment of traditional villages before 2022 [46, 47], the built environment images from 2022 provide a more accurate reflection of traditional environment characteristics.

The process involved obtaining the dominant colors and K-Means values for environmental elements in different regions through another round of K-Means clustering. Subsequently, the difference fluctuation range (called Delta E) between the K-Means value and the true color value of environmental elements was computed using CIEDE2000 algorithm. The outcome resulted in a total of 24 characteristics for the 4 geographic regions (Table 2). Each region encompasses 6 environmental elements, with each element corresponding to its K-Means value and Delta E. K-Means value represents the RGB value of the color clustering center for environmental elements, while Delta E denotes the fluctuation range of the distance between the true color value and the K-Means value.

Based on the K-Means values and Delta E of the environmental elements, substantial color differences are observed in the pond and wall elements. The color of the pond is notably influenced by its surroundings, leading to a pronounced difference in K-Means values and the largest fluctuation interval of Delta E, ranging from 37.901 to 56.845.

The dominant colors of wall elements exhibit significant differences, demonstrating varied stability. The K-Means values for northern and eastern walls are similar, presenting a light brown [RGB: (159, 151, 136), (163, 159, 147)]. On the other hand, the K-Means values for southwestern and central walls differ more, displaying a grayish-brown [RGB: (132, 127, 119)] and light yellow [RGB: (190, 182, 161)], respectively. In terms of color variation, the north and southwest exhibit greater fluctuations$[\Delta E_{north} \leq 35.029,\ \Delta E_{southwest} \leq 34.545]$, while the east and center show less variability $[\Delta E_{east} \leq 24.853,\ \Delta E_{center} \leq 22.134]$.

Moreover, the color data of roof, road, earth, and plants elements demonstrate similarities between regions, featuring smaller differences in K-Means values. The color variation ranges for these elements are more concentrated.

Table 2 The K-Means value and Delta E of element features in 4 geographical areas

Region	Selected village	Elements	K-Means value	Delta E
North	Dawuyuan village	Wall	(159, 151, 136)	ΔE ≤ 35.029
	Xiaoqiyuan village	Roof	(150, 142, 128)	ΔE ≤ 34.163
		Road	(187, 181, 168)	ΔE ≤ 21.227
	Fuling village	Earth	(156, 149, 135)	ΔE ≤ 27.346
		Pond	(102, 103, 100)	ΔE ≤ 43.084
	Dongchong village	Plants	(123, 120, 109)	ΔE ≤ 37.330
East	Longmenhe village	Wall	(163, 159, 147)	ΔE ≤ 24.853
	Pailou village	Roof	(150, 146, 131)	ΔE ≤ 43.203
		Road	(206, 200, 189)	ΔE ≤ 14.182
	Liujiawan village	Earth	(146, 140, 122)	ΔE ≤ 30.896
		Pond	(85, 86, 69)	ΔE ≤ 51.634
	Wangjiafan village	Plants	(126, 129, 114)	ΔE ≤ 35.454
Center	Shiqiaoyuan village	Wall	(190, 182, 161)	ΔE ≤ 22.134
		Roof	(132, 124, 105)	ΔE ≤ 36.587
	Lishushan village	Road	(206, 200, 189)	ΔE ≤ 14.182
		Earth	(140, 130, 104)	ΔE ≤ 35.507
	Dongyuan village	Pond	(81, 76, 51)	ΔE ≤ 56.845
		Plants	(134, 126, 101)	ΔE ≤ 38.032
Southwest	Fuxingwan village	Wall	(132, 127, 119)	ΔE ≤ 34.545
	Yatoushan village	Roof	(126, 126, 122)	ΔE ≤ 36.588
	Xinhua village	Road	(186, 182, 171)	ΔE ≤ 20.252
	Xiedian village	Earth	(154, 151, 148)	ΔE ≤ 26.525
	Longjing village	Pond	(120, 123, 116);	ΔE ≤ 37.901
		Plants	(99, 104, 98)	ΔE ≤ 43.373

Color changes of traditional village environmental elements

Using Dongyuan Village as a case study, a comparison of diachronic color data from 2017 to 2022 is conducted to analyze color changes over this period. The K-Means value derived from clustering is reassigned to image pixel points within the clusters, and the image is segmented to visualize the distribution range of each dominant color. The percentage of each dominant color on the image is calculated, allowing for an analysis of the color change in Dongyuan Village.

Figure 7 illustrates the image distribution of color data in Dongyuan Village over time. The color data distribution in the image predominantly concentrates in 8 areas:

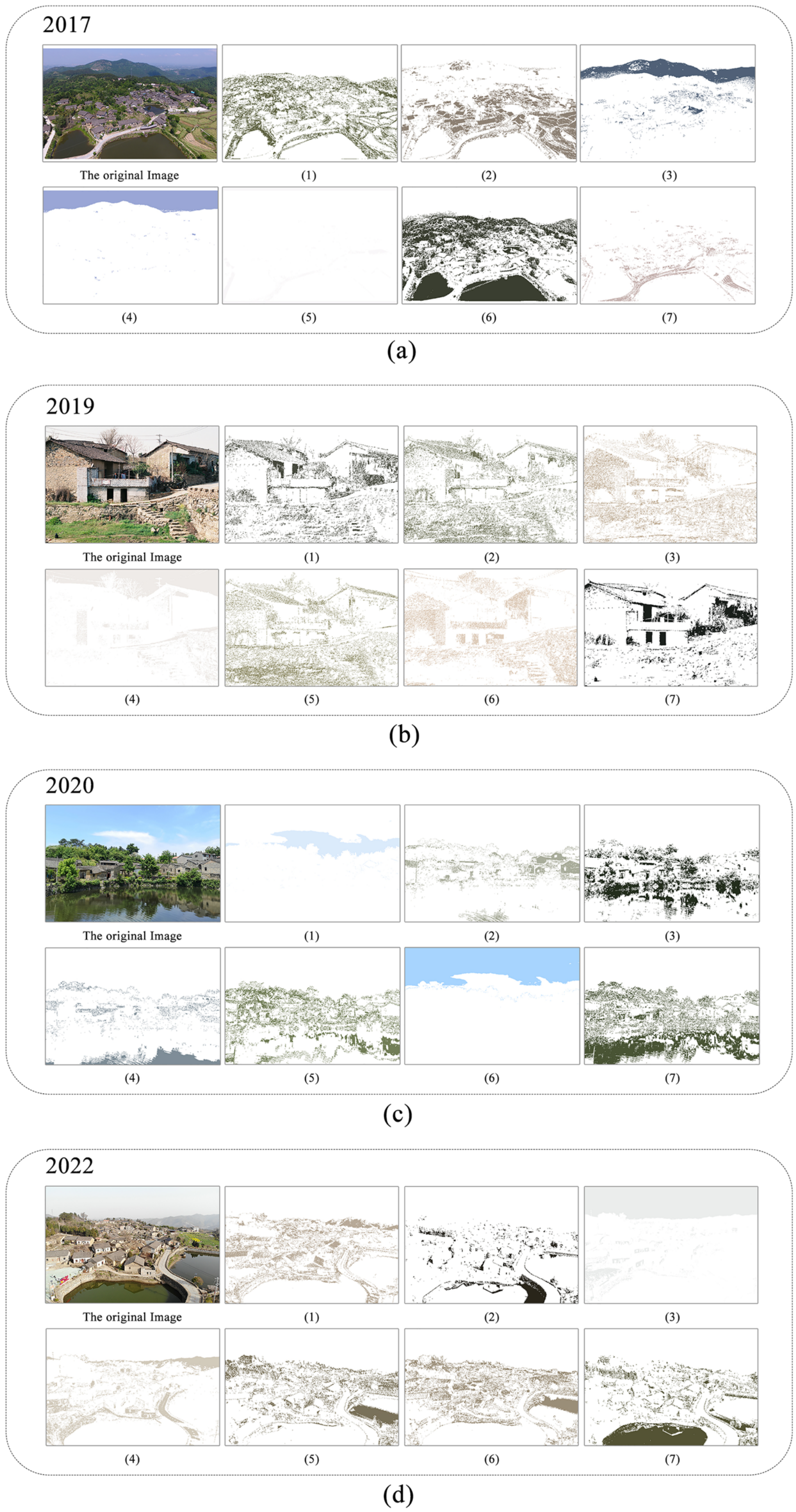

Fig. 7 Distribution of diachronic color data in Dongyuan Village. **a** 2017. **b** 2019. **c** 2020. **d** 2022

Table 3 The statistics of the dominant color ratios in Dongyuan Village from 2017 to 2022

Village	Time	Color and Ratio		
		Color	RGB Value	Ratio
Dongyuan Village	2017		(58, 62, 48)	30.5%
			(141, 129, 116)	16.3%
			(153, 166, 213)	14.7%
			(198, 178, 176)	4.8%
			(250, 247, 249)	6.7%
			(80, 97, 119)	11.0%
			(95, 99, 67)	16.0%
	2019		(73, 84, 53)	21.0%
			(166, 212, 254)	28.2%
			(114, 126, 87)	13.4%
			(126, 141, 151)	7.5%
			(35, 45, 28)	13.8%
			(169, 173, 155)	7.1%
			(219, 235, 252)	9.0%
	2020		(26, 31, 28)	11.0%
			(222, 204, 186)	15.2%
			(149, 146, 111)	15.1%
			(239, 235, 232)	20.5%
			(190, 171, 147)	13.1%
			(111, 114, 87)	13.6%
			(71, 74, 62)	11.6%
	2022		(167, 149, 103)	9.4%
			(213, 219, 230)	40.2%
			(66, 60, 34)	14.4%
			(16, 28, 32)	7.1%
			(99, 89, 52)	13.1%
			(202, 186, 144)	4.9%
			(133, 118, 74)	10.9%

roof, wall, road, pond, plants, earth, sky, and shadow. Notably, the sky and shadow elements form a single color cluster. In contrast, environmental elements within traditional villages exhibit a distribution across multiple color clusters. For example, the roof element is present in five color clusters, and certain color data share similarities with those of the plant element. Overall, this complexity in color distribution changes results from the combination of the inherent color richness within a single element and the color similarities among different elements.

Table 3 presents the proportions of different dominant colors in the images from 2017 to 2022 for Dongyuan Village. Notably, the proportion of certain dominant colors in the diachronic images of Dongyuan Village experiences minimal fluctuations over time. For instance, the data for brown and earthy yellow (which share similar RGB values) consistently hover around 35% of the color percentage in images across different time periods. This observation underscores the continuity and stability of the built environment colors in Dongyuan Village.

Based on the results of color data distribution and percentage, the color changes in different environmental elements of Dongyuan Village from 2017 to 2022 are illustrated in Fig. 8. Overall, the color of wall and road elements undergoes notable transformations.

Specifically, the dominant color of walls changes from blue [RGB: (138, 154, 213)] to yellow [RGB: (223, 206, 196)] and stabilizes. Simultaneously, the dominant color of the road gradually shifts from dark gray [RGB: (177, 164, 174)] to light gray [RGB: (239, 238, 243)]. In contrast, the color data of the shadow, pond, sky, and earth elements remain stable. The dominant color of the plants element experiences a change from green to brown, influenced by seasonal variations. Additionally, the roof element undergoes a slight color variation, influenced by the color of the surrounding environment.

Discussion

Analysis of results

In this study, we employed K-Means and CIEDE2000 algorithms to extract and analyze the color data of traditional villages built environment, focusing on color changes and regional distribution characteristics. We obtained and further interpreted the differences of color characteristics in 4 regions of Macheng City, and the trend of color changes over time in Dongyuan Village.

Algorithms for traditional village color

Due to technical and data limitations, previous studies on quantitative analysis of vernacular built heritage color have primarily relied on the extraction of dominant colors. Various clustering algorithms, such as K-Means, SVM, etc., have been utilized to extract theme colors from the built environment [25, 31, 48]. However, it is important to recognize that the color performance of built environments is influenced by a multitude of factors, resulting in both stability and diversity [27]. Consequently, the dominant color of the built environment is not static but exhibits a certain range of fluctuation. This

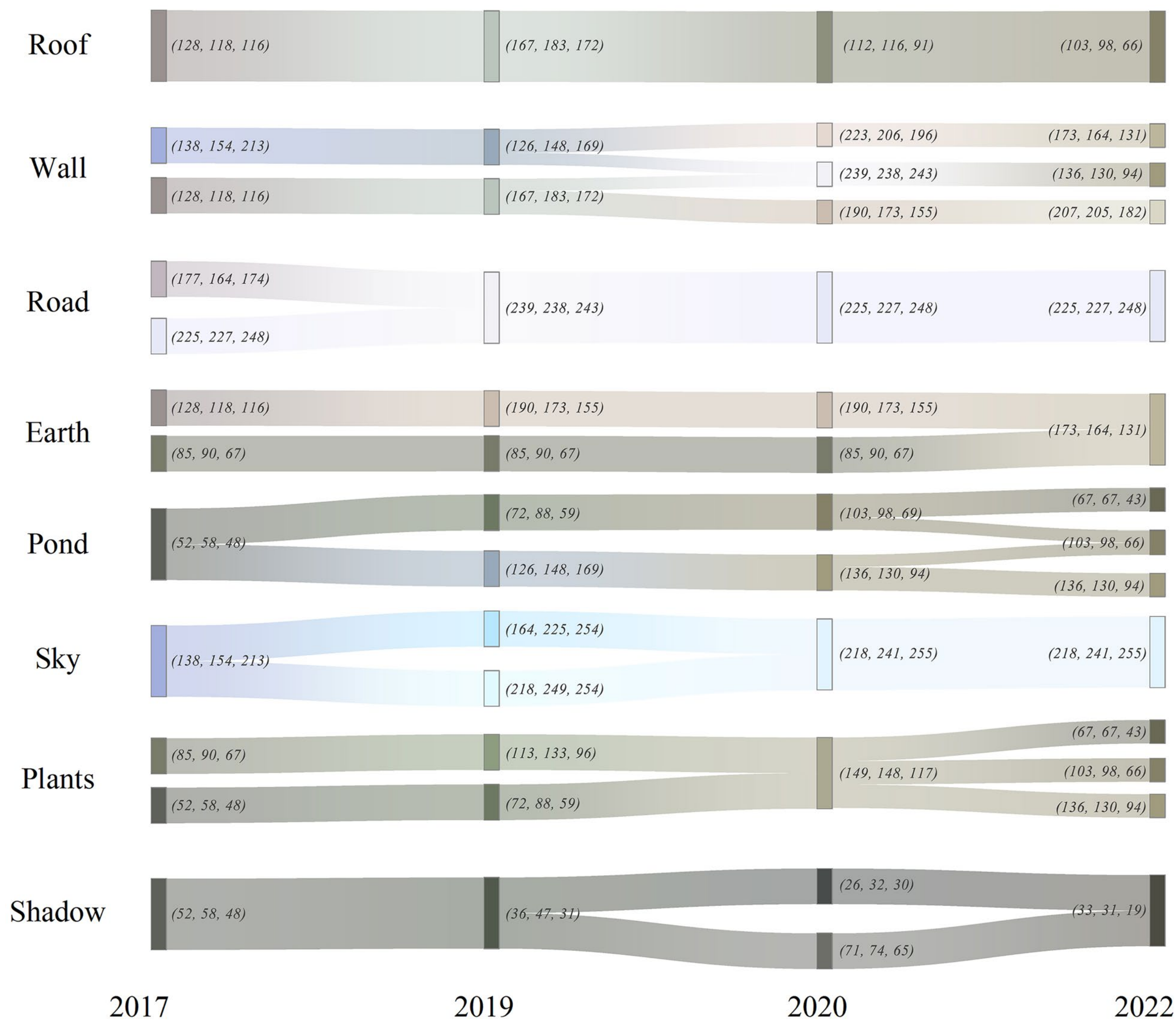

Fig. 8 The color changing trends of the environmental elements in Dongyuan Village from 2017 to 2022

variability poses a challenge to the accuracy of quantitative color analysis in vernacular built heritage.

To address this challenge, the CIEDE2000 algorithm was introduced in this study to calculate the color difference between the true color and the dominant color, thus forming corresponding fluctuation intervals. Unlike previous studies that extracted only the theme color, this method incorporates fluctuation intervals to reflect the elastic change between the dominant color and the true color. By combining the CIEDE2000 algorithm with the K-Means algorithm, this approach accurately characterizes the color dynamics of vernacular built heritage. This enhanced understanding can facilitate the formulation of color conservation recommendations and strategies to preserve vernacular built heritage effectively.

Regional characteristic differences and diachronic changes

Analyzing the color condition of the built environment through data collection and computation constitutes a significant aspect of vernacular built heritage conservation. While previous studies have primarily focused on assessing the harmony between buildings and their surrounding environment, as well as color perception within villages [27, 49], little attention has been given to analyzing diachronic changes in village color and regional characteristic differences. This study proposes an analysis of regional characteristic differences in Macheng traditional villages and temporal color changes in Dongyuan Village. By conducting such analysis, we gain a comprehensive understanding of the overall color characteristics of traditional villages. Furthermore, this analysis facilitates a deeper exploration of color changes over time and their underlying causes during the development of traditional villages.

The analysis of regional dominant colors reveals that, with the exception of significant differences in the dominant colors of wall elements, all other environmental elements in different regions exhibit similarities. This similarity is attributed to the influence of Jiangxi immigrant culture on the establishment and development of traditional villages in Macheng. The architecture in Macheng City, inspired by Jiangxi dwellings, combined with environmental adjustments, has led to the shared environmental colors of the 16 traditional villages [50].

Regarding wall elements, the K-Means value of dominant colors for northern and eastern walls are close, displaying a light brown [RGB: (159, 151, 136), (163, 159, 147)]. In contrast, the K-Means value of southwestern and central walls vary significantly, showcasing grayish brown [RGB: (132, 127, 119)] and light yellow [RGB: (190, 182, 161)], respectively. These differences in wall element are primarily influenced by the building materials used. Traditional villages in Macheng City typically characteristic masonry wall surfaces, but in the central hilly regions, rammed earth bricks combined with stone construction are more common [33]. This phenomenon is influenced by local geological conditions. Given the abundance of stone in the central region of Macheng City, it has become one of the primary building materials in that region. Conversely, in other areas, considerations such as transportation constraints lead to the predominant use of smaller-scale bricks, which are easier to transport.

In terms of the color variation range of wall elements, the north region exhibits greater fluctuations than the southwest region[$\Delta E_{north} \leq 35.029$, $\Delta E_{southwest} \leq 34.545$], driven by different factors. In the traditional villages of northern region, wall underwent red brick repair and white stucco during development (Fig. 9a), contributing to a broader range of color variations. In contrast, traditional villages in the southwest region, with more modern concrete-built dwellings, feature exposed gray concrete on the wall surfaces, interfering the range of color variations (Fig. 9b). The causes of this discrepancy lie in the influence of local socio-economic conditions. The northern region, situated in a low mountainous area with limited transportation infrastructure and lower economic development levels, predominantly employs brick masonry in village building renovations, often painted for aesthetic enhancement. In contrast, the southwest region, located in plains with dense water networks and thriving commercial trade, sees more widespread use of modern building materials due to economic prosperity. Moreover, the presence of dense water networks increases the risk of flooding, necessitating the use of modern concrete for its durability against erosion, thus further influencing construction choices.

During the process of color change in the built environment of Dongyuan Village, a portion of colors exhibits a stable trend in image ratio and distribution. Notably, the proportion of brown and earthy yellow colors (including similar RGB values) consistently hovers around 35%. Among these, brown color is concentrated in the roof elements, while earthy yellow color is predominantly found in earth, roads, and wall elements. This suggests that, during the development of Dongyuan Village, the surrounding environment have not undergone significant changes, preserving the traditional environment.

From 2017 to 2022, Dongyuan Village experienced more pronounced changes in wall and road elements. The wall color transitioned from blue [RGB: (138, 154, 213)] to yellow [RGB: (223, 206, 196)], while the road color gradually unified to light gray [RGB: (239, 238, 243)] during the same period. The color fluctuations during this period were more influenced by government policies. Comparative analysis of diachronic images reveals that from 2017 to 2020, the color change in wall element resulted from the removal of some temporary buildings and the adjustment of whitewashing. Dongyuan Village was included in Chinese national list

(a) (b)

Fig. 9 Visualization of factors influencing the range of color variations of wall elements. **a** Villages in northern Macheng. **b** Villages in southwestern Macheng of traditional villages in 2019 [51], leading the government to remove unauthorized temporary structures and restore whitewashing on the walls to maintain the environmental characteristics of the traditional village. Concurrently, as local society and the economy developed, residents increasingly recognized the importance of preserving traditional villages as cultural heritage sites. They understood that a well-maintained built environment could significantly enhance local tourism and commercial industries. Consequently, residents took proactive measures to preserve the village's built environment. Furthermore, the gradual unification of road color was attributed to a government-led road construction policy [52].

Recommendations

Based on the findings of the analysis, the following color control recommendations are proposed for the 16 traditional villages in Macheng City:

(1) Maintain Regional Differences: Preserve the existing differences among the 4 regional color reference intervals in Macheng City. Implement targeted protection measures to control the deterioration of traditional colors in the built environment of villages.
(2) Color Correction for Modern Devices: When constructing new infrastructure and service devices, conduct color correction based on regional dominant color reference intervals. Ensure that the color of modern devices aligns with the traditional color characteristics.
(3) Material Selection for Construction: For new and renovated buildings in the vicinity of traditional villages, use materials that harmonize with the regional color characteristics. This approach ensures that the constructed buildings blend seamlessly with the traditional environment.
(4) Balancing Stability and Diversity: The color of the built environment in traditional villages undergoes fluctuations during development, influenced by various factors leading to diverse color performances. The color fluctuation range parameter (Delta E) proposed in this study helps maintain a balance between stability and diversity in built environment colors. This parameter considers the elasticity of true color changes and establishes a reference value for color control in conjunction with the dominant color. It ensures a balanced approach to traditional village color schemes, accommodating both stability and diversity throughout the development process.

Limitations and improvement

In this study, certain aspects could benefit from further refinement. Firstly, in the process of collecting image data, a larger dataset would enhance the robustness of the color data analysis. To improve the accuracy and continuity of the analysis result, consideration should be given to limiting the shooting time and angles of the images [53]. This adjustment aims to achieve a more stable representation of color feature changes over time.

Secondly, the stability of the reference interval for regional color data can be influenced by the number of sample villages. While the 16 national traditional villages in Macheng City provide a representative snapshot of regional characteristics, it is important to acknowledge the potential existence of unique cases within the region. To address this, ongoing efforts to expand the research samples will be necessary to enhance the stability of reference intervals in future studies.

Thirdly, the research scope could be expanded to consider the influence of natural conditions on the color characteristics of the built environment. Future research should encompass natural condition factors within the scope, such as vegetation type, topography, soil composition, water presence, among others [54–56], to provide a comprehensive understanding of the relationship between the built environment and its natural surroundings in shaping color dynamics.

Lastly, addressing the consistent processing of image lighting conditions is crucial for future research. To more accurately capture the color characteristics of elements in images and mitigate the influence of lighting conditions on image quality, image enhancement techniques must be employed. Among the various image enhancement methods previously studied, histogram equalization emerges as a promising approach for improving image quality [57]. This method effectively mitigates grayscale and blurring issues associated with lighting conditions and imaging quality, while preserving the overall contrast of the image.

Conclusion

This study establishes an objective and effective perspective based on the analysis of color data, providing valuable insights into regional color characteristic differences and diachronic color variations in traditional villages. While previous studies have initiated the use of algorithms to compute color features, they may be constrained by calculation conditions and results, often failing to consider the elastic changes and fluctuations in real environmental colors. In contrast, our approach combines the K-Means and CIEDE2000 algorithms to establish a more effective method for analyzing the color characteristics of traditional village built environments.

By employing clustering to derive the K-Means value of architectural and environmental elements, our method calculates the difference range between the true value and the K-Means value. This innovative approach offers the opportunity to analyze the color stability and diversity of traditional village built environments, thereby uncovering the mechanisms behind diachronic changes and regional characteristic differences more comprehensively.

We conducted a case study in Macheng City, Hubei Province, to analyze the regional characteristics of traditional village colors across different areas of Macheng City, as well as the diachronic color changes observed in Dongyuan Village. The results are instrumental for the study of regional color characteristics and color changes over time in traditional villages, offering valuable guidance for color protection and control in traditional environments:

(1) The comparison of color characteristics among the 4 regions of Macheng City reveals notable differences in wall elements. The dominant color of wall element in the north and east tend to be light brown [RGB: (159, 151, 136), (163, 159, 147)], while those in the southwest and central regions are characterized by grayish-brown [RGB: (132, 127, 119)] and light yellow [RGB: (190, 182, 161)], respectively. The fluctuations in color changes are more pronounced in the north and southwest[$\Delta E_{north} \leq 35.029$, $\Delta E_{southwest} \leq 34.545$], with smaller variations observed in the east and central regions. And we analyze the reasons: the color of the elements influenced by the government-driven, the dissemination of construction techniques and the surrounding environment, tend to be consistent within each region. The color of the wall elements is limited by the construction materials and further influenced by the subsequent development of the construction techniques.

(2) The analysis of color changes in Dongyuan Village demonstrates the stability and continuity of color data. It indicates minimal alterations in the surrounding environment during its development. However, observable color changes in the wall (from blue [RGB: (138, 154, 213)] to yellow [RGB: (223, 206, 196)]) and road (light gray [RGB: (239, 238, 243)]) elements of Dongyuan Village are linked to government-led traditional village protection policies and construction initiatives.

(3) Based on the findings, the study proposes color control recommendations for the 16 traditional villages in Macheng City: (i) Align the color characteristics of traditional villages with the dominant color reference interval of their respective regions, preserving differences between regions; (ii) Conduct color correction for modern devices in accordance with the dominant color reference interval of the region; (iii) Ensure that materials used in the construction of new and renovated buildings harmonize with the color characteristics of the region; and (iv) Maintain the stability and diversity of traditional village colors.

However, it is important to note limitations in this study, such as sample size, variations in image angles and shooting times. Moreover, natural conditions play a significant role in color characteristics. To improve future studies, we recommend including factors like vegetation, terrain, soil, and water to better understand their impact on color changes.

Author contributions

GT: Reviewing and Editing. ZC: Investigation, Experiment, Methodology, Data analysis, Writing-Original draft preparation. MX: Preparing pictures and tables. YJ: Conceptualization, Writing.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

The consent for the publication of details and images in the manuscript are obtained from all participants.

Competing interests

The authors declare no competing interests.

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