Restoration Method of Sootiness Mural Images Based on Dark Channel Prior and Retinex by Bilateral Filter

Ning Cao
Beijing University of Civil Engineering and Architecture
Shuqiang Lyu
Beijing University of Civil Engineering and Architecture
Miaole Hou (houmiaole@bucea.edu.cn)
Beijing University of Civil Engineering and Architecture
Wanfu Wang
Dunhuang Research Academy
Zhenhua Gao
Beijing University of Civil Engineering and Architecture
Ahmed Shaker
Ryerson University
Youqiang Dong
Beijing University of Civil Engineering and Architecture

Research article

Keywords: mural, sootiness, hyperspectral imaging, near-infrared, dark channel prior, Retinex by bilateral filter, virtual restoration

Posted Date: November 19th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-107842/v1

Version of Record: A version of this preprint was published on March 6th, 2021. See the published version at https://doi.org/10.1186/s40494-021-00504-5.

Restoration Method of Sootiness Mural Images Based on Dark Channel Prior and Retinex by Bilateral Filter

Ning Cao [1,2], Shuqiang Lyu [1,2*], Miaole Hou [1,2*], Wanfu Wang [3], Zhenhua Gao [1,4], Ahmed Shaker [5] and Youqiang Dong [1,2]

[1] Beijing University of Civil Engineering and Architecture, No.15 Yongyuan Road, Daxing District, Beijing 102616, China

[2] Beijing Key Laboratory for Architectural Heritage Fine Reconstruction & Health Monitoring, No.15 Yongyuan Road, Daxing District, Beijing 102616, China

[3] The Dunhuang Academy, Dunhuang 736200, China

[4] Shanxi Provincial Institute of Archaeology, Taiyuan 030000, China

[5] Ryerson university, 350 Victoria Street, Toronto ON M5B 2K3, Canada.

* Correspondence: lvshuqiang@bucea.edu.cn; houmiaole@bucea.edu.cn

Abstract: Environmental changes and human activities can cause serious degradation of murals, where sootiness is one of the most common problems of ancient Chinese indoor murals. In order to improve the visual quality of the murals, a restoration method is proposed for sootiness murals based on dark channel prior and Retinex by bilateral filter using hyperspectral imaging technology. First, radiometric correction and denoising through band clipping and minimum noise fraction rotation forward and inverse transform were applied to the hyperspectral data of the sootiness mural to produce its denoised reflectance image. Second, a near-infrared band was selected from the reflectance image and combined with the green and blue visible bands to synthesize a pseudo color image for the subsequent sootiness removal processing. The near-infrared band is selected because it is better penetrating the sootiness layer to a certain extent comparing to other bands. Third, the sootiness covered on the pseudo color image was preliminarily removed by using the method of dark channel prior and by adjusting the brightness of the image. Finally, the Retinex by bilateral filter was performed on the image to get the final restored image, where the sootiness was removed. The results show that the proposed method can effectively reduce the influence of sootiness on the mural image and improve its visual quality. It can also be used to reveal the original appearance of the mural to reasonable extent.

Keywords: mural; sootiness; hyperspectral imaging; near-infrared; dark channel prior; Retinex by bilateral filter; virtual restoration

1. Introduction

As one of the most important components of cultural heritage, murals have profound historical significance and research value [1]. Temple murals are part of the dominant types of Chinese murals, usually painted on the walls of Buddhist or Taoist temples. However, murals deteriorated to different degrees due to the changes of the environment and human activities. Burning incense while praying in temples were very common phenomena for a long period of time, which made temple murals vulnerable to sootiness, resulting in blurred patterns. At present, the study on the sootiness mural is mainly focused on the influence of the sootiness on the pigments in the mural [2] and the sootiness cleaning [3]. Traditional methods of removing sootiness mostly use chemical reagents, which are tedious, time-consuming and laborious, and the chemical reagents may cause a certain degree of damage to cultural relics. Therefore, it has become a research hotspot of mural digital protection to virtually repair the degradation of mural quality and restore the original appearance of mural by using digital photography technology.

In recent years, the study on virtual restoration of murals mostly focuses on the automatic filling method of damaged areas. For example, Wang, 2015 [4], used the method of directions for dictionary learning, and realized the informatization and restoration of the murals in Potala Palace by sparse representation, so that the restored images can better retain the details and edge information in the murals. However, the proposed method only restored the simulated missing pixels in the mural image, and did not restore the real mural image. Li et al., 2016 [5], used threshold segmentation to extract the mud spots based on the characteristics of brightness, colourity and texture of the mud spots on the mural of Tang Dynasty tomb, which improved the accuracy of mud spots extraction, and used the existing Criminisi algorithm to inpaint the mud spots. Jaidilert et al., 2018 [6], used region growing and morphological methods to detect scratches in Thai murals based on seed points provided by users, which improved the accuracy of scratch extraction, and used the existing variational inpainting methods to restore the scratches. Although, the above two methods mainly focused on the detection and extraction methods of mud spots and scratches, and used existing inpainting methods to restore some simple damaged areas, there were little research on restoration algorithm.

Purkait et al., 2017 [7], used patch similarity measurement method based on spatial coherence to improve patch-based restoration algorithm to achieve automatic coherent texture synthesis, and completed the inpainting of colorful Indian temple murals. Shen et al., 2017 [8], improved the morphological component analysis method based on sparse method to decompose the image into structure and texture parts, and simplified total variation algorithm and K-singular value decomposition algorithm. As a result of applying the described method, the authors were able to inpaint the cracks in the murals and improve the inpainting accuracy. Wang et al., 2018 [9] improved the algorithm of Criminisi by using the wavelet energy factors and virtually restored the scratches and paint losses of Ming Dynasty murals in Guanyin Temple, Xinjin County, Sichuan Province, China, so that the overall texture and color of the restored murals were continuous and natural. Cao et al., 2020 [10], proposed a consistency enhanced generative adversarial network model, which achieved the restoration of the temple murals in Wutai Mountain, China, so that the overall consistency and structural continuity of the restored images were better. However, at present, most of the virtual restoration methods were aimed at problems such as paint losses and cracks, and there are few methods to restore the sootiness murals.

Distinct from other problems, the sootiness usually covers a large area on mural, and its spatial distribution is similar to foggy images. The current study on image defogging algorithms mainly includes the following two types of methods [11]. The first one is based on image enhancement, such as histogram equalization method [12] or the enhancement method based on Retinex method [13-15]. The method based on the enhancement only enhances the contrast of image without considering the cause of image degradation. It can effectively improve the visual effect, but the resulting image will appear as information loss and oversaturation. The second one is the image defogging algorithm based on the physical imaging model [16,17]. This method can restore the image to its original state before degradation based on physical imaging model, which makes the image more natural. However, due to the lack of known information, the image defogging is uncertain and prone to halo phenomenon.

With the development of remote sensing technology, hyperspectral imaging has been widely used in many fields. It can provide spectral information with high spectral resolution and nearly continuous spectral curve for each pixel of the image. It can usually cover visible light to near-infrared wavelength, which is helpful to identify the information covered by pigments or surface materials, and to mine the information that is difficult to be recognized by human eyes [18]. Because of these unique advantages, hyperspectral imaging technology has been introduced into the study of cultural relics protection, including virtual restoration [19,20] and visual enhancement [21-25], which adds potential to the use of the hyperspectral technology to remove sootiness from murals.

The main objective of this study is to propose an effective method to improve the visual quality of ancient mural images and restore the sootiness murals by using hyperspectral imaging technology and related defogging methods. In the proposed method, the hyperspectral data of sootiness mural are acquired by the hyperspectral imaging system and the data preprocessing is carried out by radiometric correction and data denoising. The sootiness mural image is then synthesized by combining the near-infrared band. Finally, the restoration of sootiness mural is completed by the method of dark channel prior and the Retinex by bilateral filtering.

2. Materials and Restoration Methods

2.1. Materials

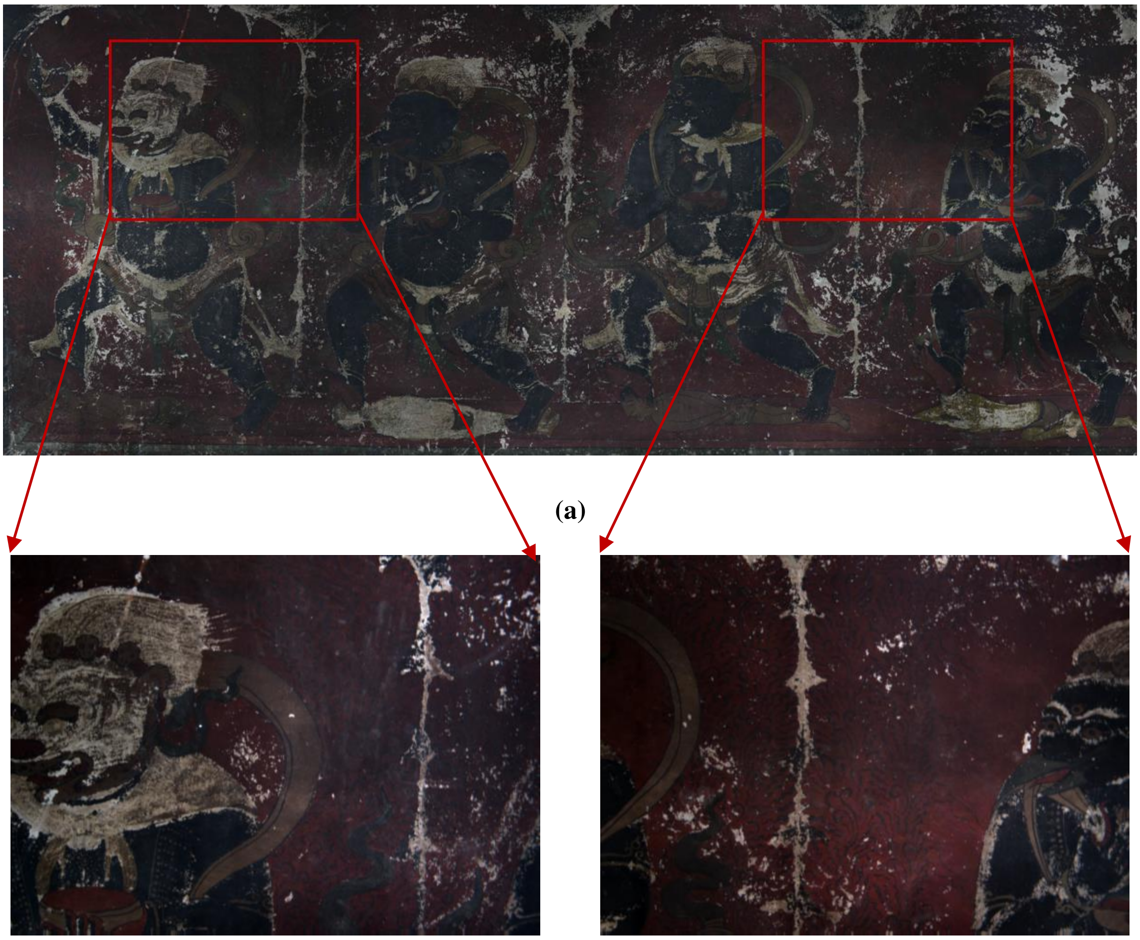
2.1.1. Sootiness

According to the Chinese National Standard for the Protection of Cultural Relics, *Ancient wall painting deterioration and legends* (GB/T 30237-2013) [26], sootiness is the mark of the mural being polluted by soot or incense, as shown as an example, in Figure 1. Due to the contamination of sootiness, the patterns in the murals are often blurred, which seriously affects the value of appreciation of the murals.

Figure 1. Sootiness legend of mural.

2.1.2. Mural Data

The mural selected in this study is located on the north indoor wall of Daheitian Hall on the east side of Qutan Temple, located at Ledu District, Haidong City, Qinghai Province, China. According to the site's records in China, the temple was built in the 25th year of Minghongwu (1392 A.D.), with a history of more than six hundred years [27]. As shown in Figure 2a, due to the activities of incense burning and worship Buddha for a long time, the mural is seriously contaminated by sootiness. Some of the patterns in the mural are covered and cannot be recognized by the naked eye. In order to reduce the influence of sootiness on the mural and restore the information covered by sootiness, the hyperspectral data of the mural were captured and analyzed.



(b) (c)

Figure 2. The image of the mural and the two study areas: (a) complete image of the mural; (b) image of the first study area; (c) image of the second study area.

2.1.3. Data Acquisition

In July 2018, the mural data of the study areas were captured by using the VNIR400H hyperspectral imaging system of Themis Vision Systems with the spatial resolution 1392 × 1000 pixels and 1040 bands covering from 377.45 nm (visible light) to 1033.10 nm (near-infrared). The spectral sampling interval was 0.6 nm, and the spectral resolution was 2.8 nm.

During the data acquisition, the distance between the hyperspectral camera and the mural was about 1 m. The sunlight was blocked by closed doors and windows, and a pair of halogen lamps whose spectral distribution is close to that of sunlight were used for illumination. A total of 24 hyperspectral images were collected, covering most of the sootiness area of the north wall of the Daheitian Hall. The images of the two study areas, shown in Figure 2b,c, are the true color images synthesized by the red, green and blue bands with wavelengths of 460.20 nm, 549.79 nm and 640.31 nm after radiometric correction and data denoising.

2.2. Restoration Method

Figure 3 shows the overall workflow of the proposed method for the restoration of sootiness mural images, including four main steps: (1) Data preprocessing using radiometric correction and data denoising, (2) sootiness mural image synthesis using block histogram matching of pseudo color image and true color image, (3) preliminary sootiness removal using dark channel prior and image brightness adjustment, and (4) restoration of sootiness mural using Retinex by bilateral filter in HSV (hue, saturation, value) color space. The details of each step are discussed in the following sections.

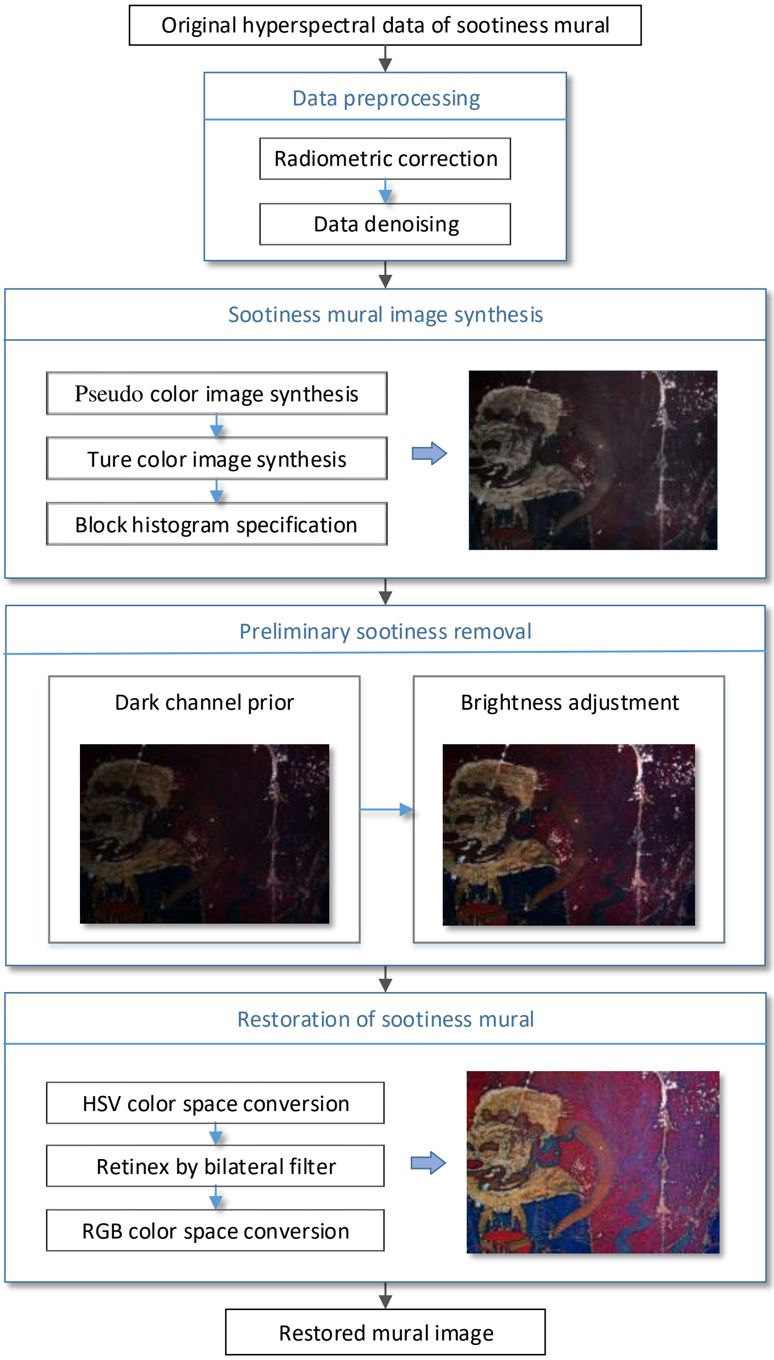


Figure 3. The overall workflow of the proposed method.

2.2.1. Data Preprocessing and Sootiness Mural Image Synthesis

The original data captured by hyperspectral imaging system are in radiance and the data range is depending on the number of digitalization bits of the system. Before the next step of the analysis, it is necessary to convert the radiance into reflectance image. Therefore, the reflectance of the original hyperspectral data were corrected using the following equation:

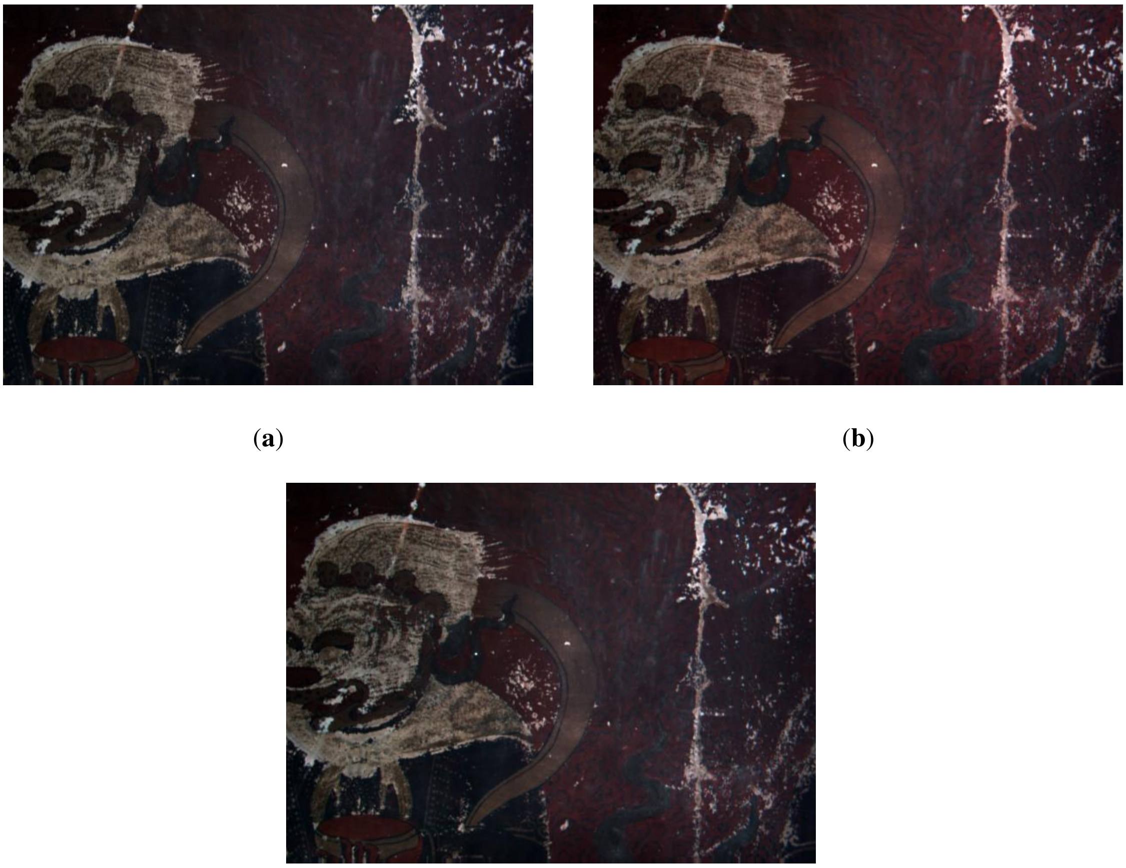
$$\mathrm{R} = \frac{R_{raw} - R_{dark}}{R_{white} - R_{dark}} \quad (1)$$

Where, R is the corrected reflectance image; R_{raw} is the original image of the mural; R_{white} is the standard reflector data obtained on site; and R_{dark} is the dark current data acquired with the light source off and the lens covered. The reflectance of the standard reflector is 99%.

In addition, in the data acquisition of hyperspectral imaging system, there will be some noise bands due to the changes of environmental parameters and the interference of dark current noise. Through the inspection of the data, it was found that the bands at both ends of the sensor's wavelength spectrum were noisy, that is, the bands with the shortest wavelength and the bands with the longest wavelength. After observing the spectral curve of random pixels on the image, the 51-990 bands (405.79-1000.79 nm) were manually selected for subsequent processing in the 1040 bands acquired.

In order to further reduce the noise, the selected data were processed by the minimum noise fraction rotation (MNF), which is a common method of dimension reduction and denoising in hyperspectral data processing [28]. It can transform the noise covariance matrix of the data and the noise whitening data, and retain the principal component with relatively large signal-to-noise ratio, so as to realize the dimensionality reduction and denoising of hyperspectral data. In this paper, the MNF transformation was performed on the hyperspectral data after manual selection to separate the noise from the information in the data. The top n components with more than 95% information content were selected for inverse MNF transformation, and the hyperspectral data dimension was restored, and the data denoising was realized.

It was observed that the near-infrared bands can reveal the information under the surface material coverage to a certain extent, which is conducive to the removal of sootiness. Therefore, the near-infrared, green and blue bands with wavelengths of 845.77 nm, 549.79 nm and 460.20 nm were selected to synthesize a pseudo color image (PCI) in the denoising hyperspectral image. The red, green, and blue bands with wavelengths of 640.31 nm, 549.79 nm, and 460.20 nm were selected to synthesize a true color image (TCI). However, by comparing the image quality of PCI and TCI, it was found that some of the patterns in the murals were clearer and more realistic in the TCI. Thus, PCI was calibrated to obtain the sootiness mural image (SMI) by block histogram matching method which adopted the TCI as the reference, as shown in Figure 4. In the following sections, the TCI is used as a reference image in comparison of restoration effect. The PCI is used to obtain the dark channel image in the dark channel prior sootiness removal, so as to solve the atmospheric light value and transmittance. SMI is used as the sootiness mural image to be restored for the subsequent restoration of sootiness mural.



(**a**) (**b**)

(**c**)

Figure 4. The synthetic hyperspectral image of area 1: (a) true color image (TCI); (b) pseudo color image (PCI); (c) sootiness mural image (SMI).

2.2.2. Dark Channel Prior and Brightness Adjustment

According to the similarity between sootiness mural images and foggy images, the method of dark channel prior defogging was applied to preliminary remove of sootiness in mural images. In computer vision and computer graphics, the atmospheric scattering model is usually used to describe the formation process and method of foggy images. Although the particles of sootiness and fog are different, they will cause some light to be scattered by the particles and the light intensity will be weakened when the incident light contacts with the particles, such as equation (2) [29]:

$$\mathrm{S(x) = D(x)t(x) + A\big(1 - t(x)\big)} \tag{2}$$

Where:

$\mathrm{S(x)}$ is the sootiness mural image to be restored;

$\mathrm{D(x)}$ is the image of target scene after sootiness removal;

$\mathrm{t(x)}$ is the medium transmittance of the sootiness;

A is the atmospheric light value.

The purpose of the restoration of sootiness mural is to recover D, A and t from S.

The dark channel prior is a statistical rule proposed by He et al. [16], and equation (2) can be solved by using the dark channel prior. It points out that in most fog-free images (non-sky areas), there will be some areas, at least one color channel has some pixels whose intensity are very low and close to zero. This channel is called dark channel. Such as the shadow of objects, dark objects, or objects with colors close to one of red, green, and blue, etc. The mathematical expression is as follows:

$$P^{dark}(x) = \min_{z\in\Omega(x)}\big(\min_{c\in(r,g,b)} P^{c}(y)\big) \tag{3}$$

Where:

c is a color channel among r, g, and b;

P^{C} is the gray value of a channel of P;

$\Omega(\mathrm{x})$ is a local patch centered at x.

A dark channel image is the result of two minimum operators:

$\min\limits_{c\in(r,g,b)}$ is the minimum value of each pixel in the $\mathrm{r, g, b}$ channel,

$\min\limits_{z\in\Omega(x)}$ is a minimum filter.

The minimum filter will replace the value of a given pixel with the minimum value among the values of this pixel and its surrounding pixels. The number of surrounding pixels, i.e. the filter size, can be specified by the user. According to the method of dark channel prior, for the fog-free image, the dark channel is $P^{dark} \to 0$.

In the proposed method, the sootiness removal of the SMI was carried out by combining the PCI, atmospheric scattering model and dark channel prior method. First, estimate the atmospheric light A. The dark channel image $P^{dark}(x)$ was calculated by the PCI, and the maximum value of dark channel was selected as the estimated value of atmospheric light. Second, calculate the transmission t. When the atmospheric light value had been obtained, according to the dark channel prior and the atmospheric scattering model, the transmission t can be obtained. The constant parameter ω ($0 < \omega \leq 1$) was introduced to retain the perspective depth of the image and make it more realistic:

$$t(x) = 1 - \omega \min_{c}(\min_{y \in \Omega(x)}(\frac{P^c(y)}{A^c})) \tag{4}$$

Third, restore the image D(x) after sootiness removal. After the atmospheric light value A and transmittance t were obtained, the SMI was taken as the S(x) to be restored, and then the image D(x) after sootiness removal was solved according to the atmospheric scattering model. When the transmission approached zero, direct recovery of D(x) was prone to noise. Therefore, the minimum threshold t_0 was set to control the transmission, so:

$$D(x) = \frac{S(x) - A}{\max(t(x), t_0)} + A \tag{5}$$

Finally, the brightness of the image D(x) was low after removing the sootiness via the dark channel prior, so the image was converted to the HSV color space, and the image brightness was adjusted by setting a brightness factor and multiplying it with the Value component. Thus, the mural image B(x) with preliminary sootiness removal was obtained, and the details of the mural were enhanced while removing the interference of sootiness.

2.2.3. Retinex by Bilateral Filter in HSV Color Space

In order to further remove the sootiness from mural image, defogging method of Retinex by Bilateral Filter is applied to the sootiness mural image. Retinex method considers the brightness of the object perceived by the human eye as an organic combination of the illumination of the environment and the reflection of the object surface [30]. The illumination component can be estimated from the original image to obtain the reflection component, that is, the color of the object itself. The mathematical expression of Retinex method is:

$$B(x) = R(x) \cdot L(x) \tag{6}$$

Where, B(x) is the image pixel value received by the human eye or camera, that is the image after preliminary sootiness removal in the proposed method; illumination image L(x) is the illumination component of the ambient light; and reflection image R(x) is the reflection component of the object.

Bilateral filter [31] is a nonlinear filter, which combines the spatial proximity and pixel similarity of image, and can consider both spatial information and gray similarity. Compared with Gaussian filtering, bilateral filtering can effectively remove most noise while keeping image details. During the filtering, edge keeping and denoising are better realized by adjusting the filter size p which represents the diameter of each pixel neighborhood, the weight σ_r which controls the change of gray scale, and the weight σ_s which controls the change of spatial distance.

In the proposed method, the defogging method of Retinex by bilateral Filter [14] was used to further improve the visual effect of the sootiness mural by setting two bilateral filters with different weights and parameters. First, the image B(x) after the preliminary sootiness removal was converted from RGB space to HSV color space. Second, only for Value component, the illumination image was obtained by bilateral filtering. Then, the logarithm of the original image and illumination image were taken, and the reflection image was solved by bilateral filtering according to the Retinex method, so as to obtain the recovered image of the V component. Finally, the HSV space image was converted to RGB (red, green, blue) space to realize the restoration of sootiness mural.

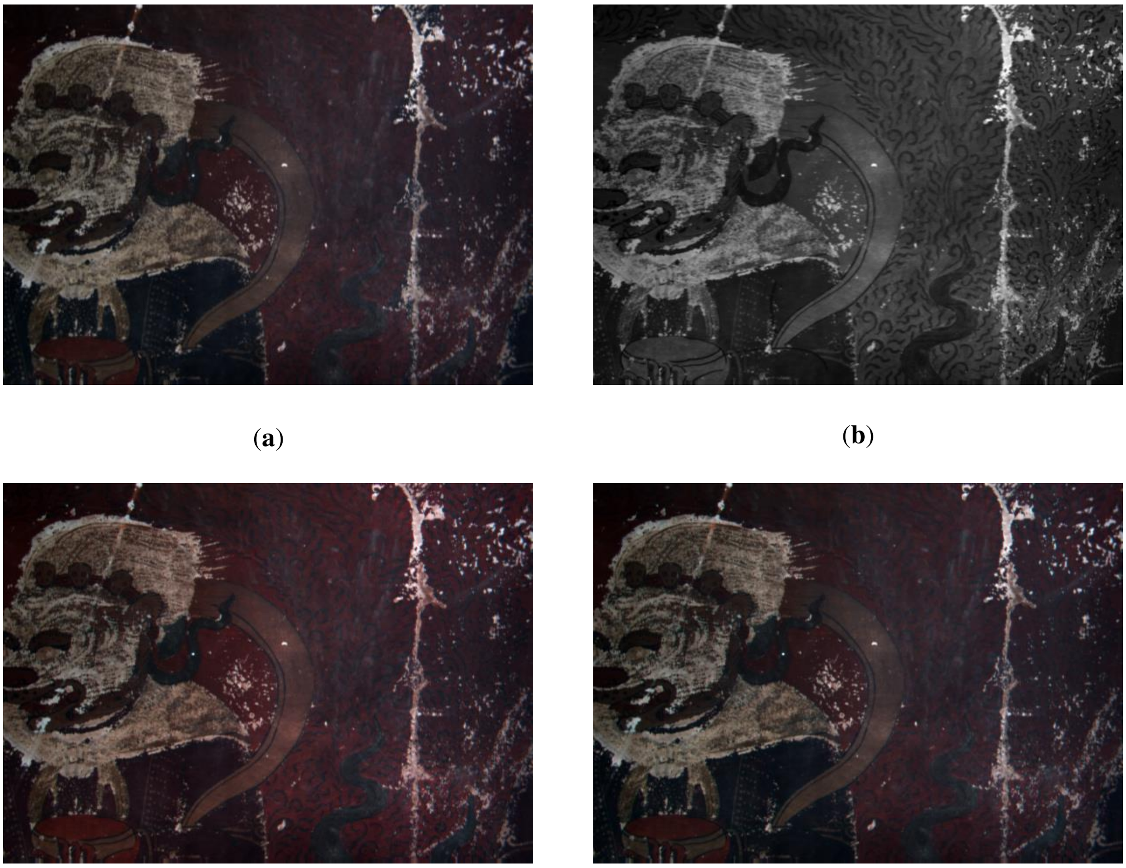
2.3 other method to be discussed

Homomorphic filtering is a method to compress the image brightness range and enhance the contrast in frequency domain [32]. It is based on the illumination and reflection model of the image. By adjusting the gray range of the image, it can enhance the detail information of the dark area without losing the details of the bright area. Gaussian stretching is an interactive histogram stretching method in radiation enhancement. By stretching the histogram of the output image into a Gaussian function, the detail information of the image is enhanced. Homomorphic filtering and Gaussian stretching will be used in the discussion and compared with the proposed method.

3. Results

3.1. Sootiness Mural Image Synthesis

As shown in Figure 5a, the mural is seriously contaminated by sootiness. The entire image is blackened, and some of the lines in the background are blurry. Figure 5b shows the near-infrared band with a wavelength of 845.77 nm in area 1. In this band, the lines on the red background were clearer, and the black marks on the edge of the white paint losses on the right side of the character disappeared. So, the three bands of near-infrared, green and blue with wavelengths of 845.77 nm, 549.79 nm and 460.20 nm were selected as red, green and blue channel to synthesize the PCI, as shown in Figure 5c. The selection of near-infrared band has little effect on the visualization of sootiness mural image. However, compared with the PCI, the clothes of the lower left part of the image were clearer and the color was more realistic in the TCI. Therefore, based on the TCI, block histogram matching was performed on the PCI. For the study areas of this article, the resolution was 1392 × 1000 pixels, and the blocking standard was to divide the image length and width into 8 equal parts, that is, the image was divided into 64 blocks, the spatial resolution of each block was 174 × 125 pixels. The smaller the block is, the clearer the clothing is, and the more realistic the color is. But if the block is too small, the black marks on the edge of the paint losses will reappear. Figure 4d shows the SMI after the block histogram matching. The black marks on the edge of the paint losses region disappeared, and the color of the clothes was more realistic.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. The synthetic sootiness mural image of area 1: (a) synthetic true color image; (b) near-infrared band image; (c) synthetic pseudo color image; (d) sootiness mural image after block histogram matching.

3.2. Preliminary Sootiness Removal

In the preliminary sootiness removal, the dark channel image was first calculated from the PCI, and the SMI was obtained after block histogram matching. Then, the sootiness removal was performed on the sootiness mural image via the dark channel prior. For the study areas of the proposed method, the minimum filter size was 3 × 3. If the filter size is too large, the sootiness removal effect will be poor, and if it is too small, some information in the image will be blurred. The dark channel image is shown in Figure 6b. The effect of dark channel priori sootiness removal is shown in Figure 6c. Finally, through the image brightness adjustment, the mural image after the preliminary sootiness removal was obtained, and the brightness factor is 2.0, as shown in Figure 6d. Compared with the TCI, the image after removing the sootiness via the dark channel prior and brightness adjustment preliminarily reduced the sootiness effect and made the black textures in the red background clearer.

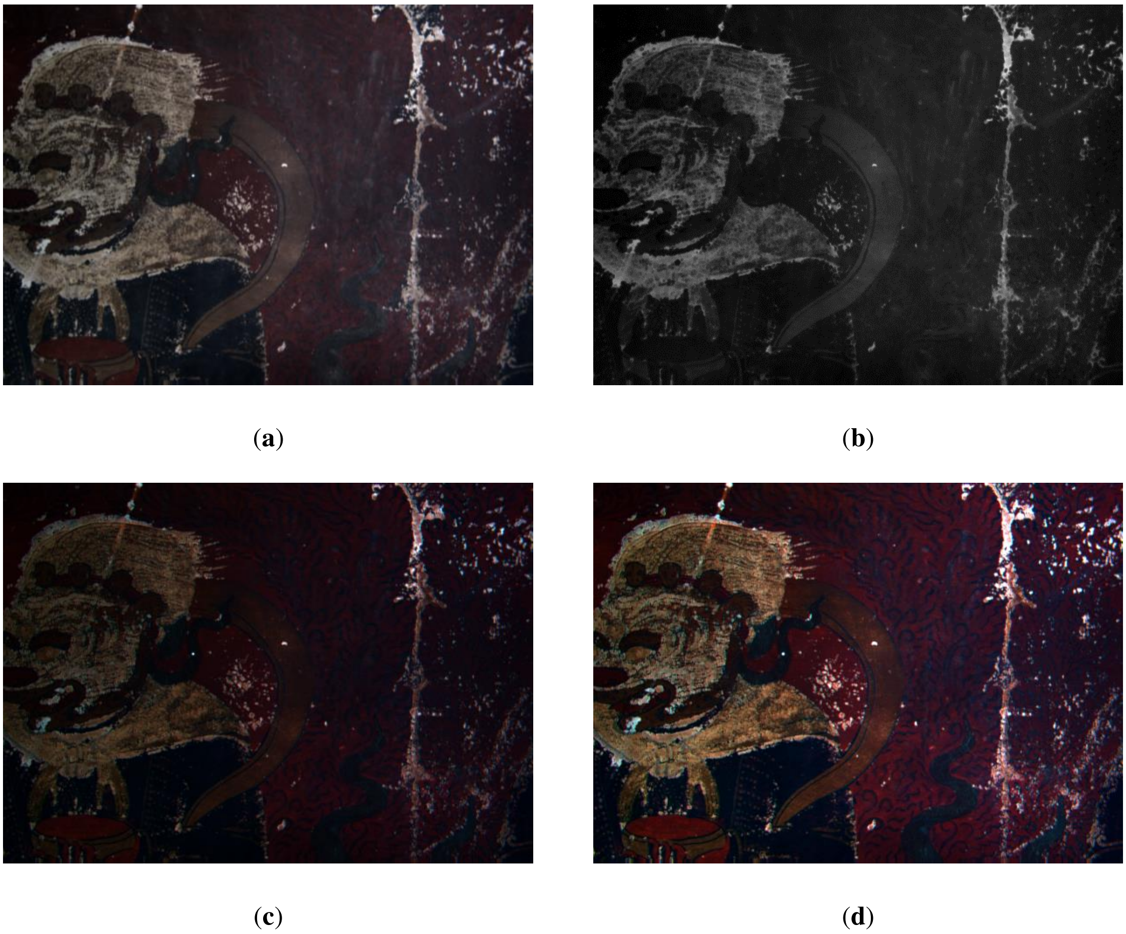


Figure 6. The preliminary sootiness removal results of area 1: (a) synthetic true color image; (b) dark channel image; (c) result of dark channel priori sootiness removal; (d) result of brightness adjustment.

3.3. Restoration of Sootiness Mural

In order to further restore the sootiness mural, the preliminary sootiness removal image obtained in the previous step was converted to HSV color space. The Retinex by bilateral Filter was used to solve the illumination image and reflection image respectively. Then the HSV space image was converted to RGB space to realize the restoration of sootiness mural. In the proposed method, the filter size p, the weight to control the change of gray scale σ_r and the weight to control the change of spatial distance σ_s of two bilateral filters are shown in Table 1. The larger the filter size is, the more obvious the denoising effect is, but it will slow down the calculation speed. The gray scale change weight and space distance weight have little influence on the restoration effect of sootiness mural image. From a visual point of view, as shown in Figure 7b, the restored image basically removed the influence of sootiness on the content of the mural. The lines at the background were clear, and the black marks on the edge of the paint losses region disappeared. The mural image was clear as a whole, and the pattern on it were more attractive. Therefore, this process can restore the blurred mural caused by sootiness contamination, increase its readability, and realize the restoration of sootiness mural.

Table 1. The parameters of Retinex by bilateral Filter.

Parameter	**p**	σ_r	σ_s
First bilateral filter	15	0.3	100
Second bilateral filter	4	0.3	100

(**a**) (**b**)

Figure 7. The restoration result of area 1: (a) synthetic true color image; (b) restoration result.

4. Discussion

4.1. Digital Image and Synthetic Hyperspectral Image

Hyperspectral image has a high spectral resolution, which is helpful for mining the information covered by surface materials. However, its spatial resolution is relatively low, so a high spatial resolution photo taken by a digital camera was used for comparative experiments. Figure 7a shows a high spatial resolution digital photo taken by Nikon DB810 camera in the study area 1, with a resolution of 4841 × 3688 pixels. The method proposed in this paper and the same parameters were used for processing. The effects are shown in Figure 8.

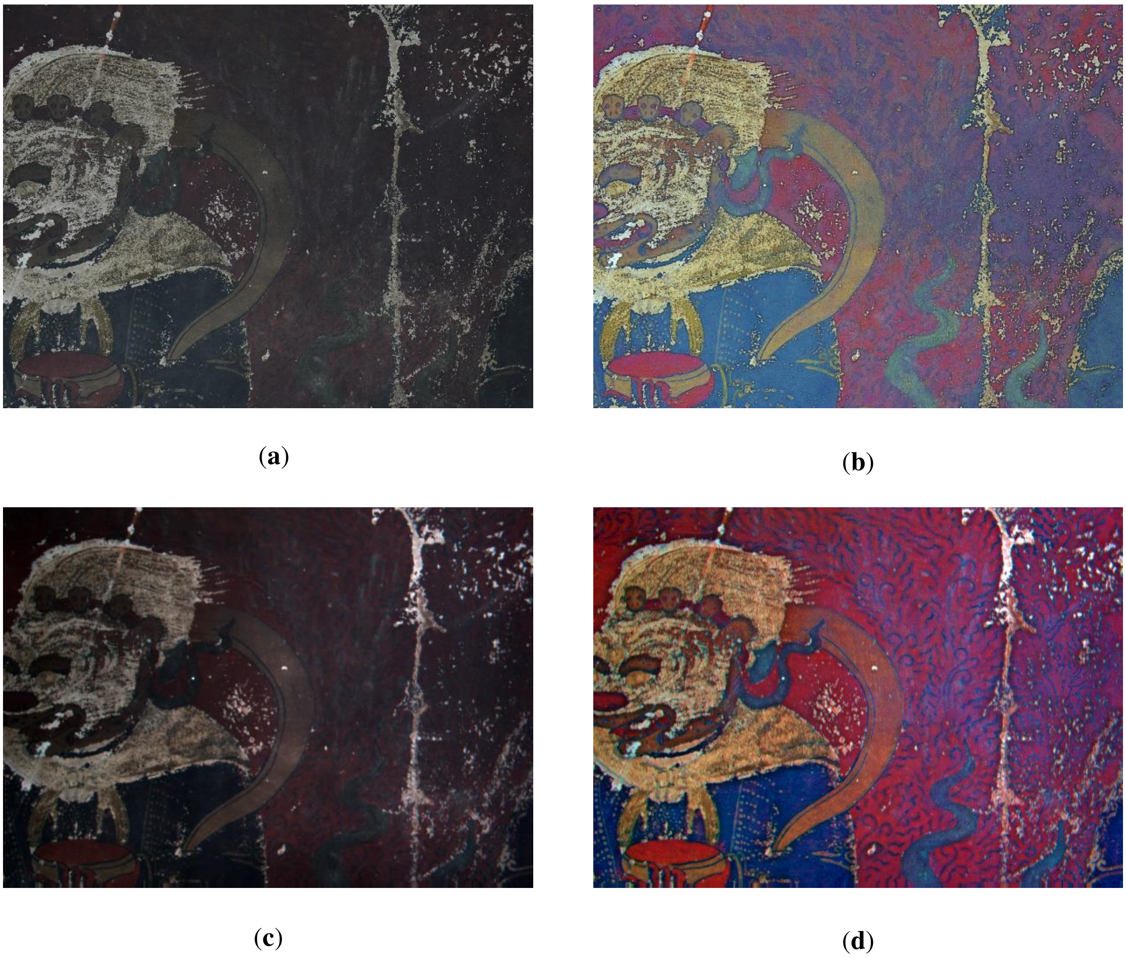


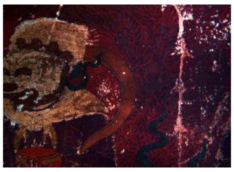
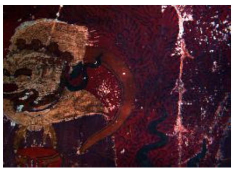
Figure 8. The restoration effects of digital photo and hyperspectral synthetic image of area 1: (a) digital photo; (b) restoration effect of digital photo; (c) hyperspectral synthetic image; (d) restoration effect of hyperspectral synthetic image.

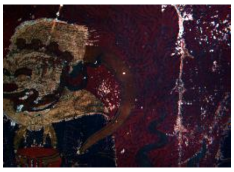
It can be seen from Figure 8 that although the image taken by the digital camera has a higher spatial resolution, its restoration effect was not as good as that of the sootiness mural image synthesized by hyperspectral. Especially for the lines located among the red region，they were clearly visible in the restored image using the hyperspectral synthetic image, but still blurred in the restored image using the digital photo.

4.2. Image Selection during the Dark Channel Prior Sootiness Removal

Due to the large number of bands provided by the hyperspectral image, it is possible to combine many images with different bands to carry out the method. In order to select the optimal S(x) and the most suitable image for calculating the dark channel image in the dark channel prior sootiness removal, the following experiments were performed. Take the TCI, the PCI and the SMI as the S(x) or the image used to calculate the dark channel image, and perform the dark channel prior to remove sootiness. In order to facilitate the observation, the brightness adjustment and the Retinex by Bilateral Filter in HSV Color Space processing were also carried out for the image after the dark channel prior sootiness removal. It can be seen from Figure a-f in Table 2 that when the PCI was used to calculate the dark channel image, the clothes and details of the character is clearer. It can be seen from Figure g-l that when the PCI was used as the image to be restored, some black masks are disappeared, such as the edge of the white paint losses area on the right side of the image. Therefore, in the proposed method, the PCI was selected to calculate the dark channel image, and the SMI as the S(x). The restoration effects were shown in Figure p-r.

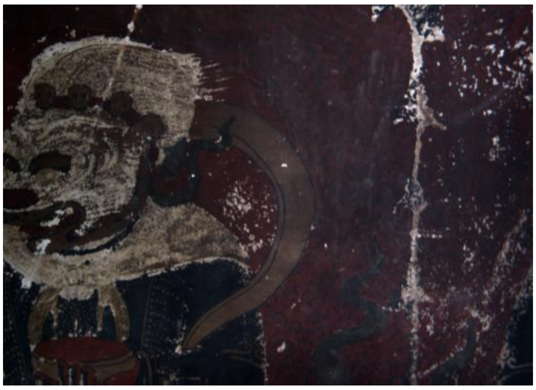
Table 2. The comparison of sootiness removal results at different steps with different image combination.

Image selection		**Results by Dark Channel Prior**	**Results by Dark Channel Prior and Brightness Adjustment**	**Results by complete method proposed**
As the Image to Calculate the Dark Channel Image	**As the S(x) in Equation (2)**			
TCI	**TCI**	 **(a)**	 **(b)**	 **(c)**
PCI	**TCI**	 **(d)**	 **(e)**	 **(f)**
PCI	**PCI**	 **(g)**	 **(h)**	 **(i)**
TCI	**PCI**	 **(j)**	 **(k)**	 **(l)**

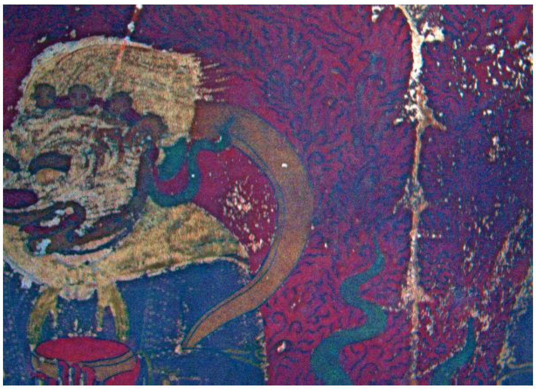
SMI	**SMI**			
		(**m**)	(**n**)	(**o**)
PCI	**SMI**			
		(**p**)	(**q**)	(**r**)

4.3. Combination of Different Steps

In order to further compare the effect of the proposed method, MNF transformation and dark channel prior sootiness removal steps were omitted, and other processing and parameters were consistent with the proposed method. The effects are shown in Figure 9.



(**a**)



(**b**)

(**c**)

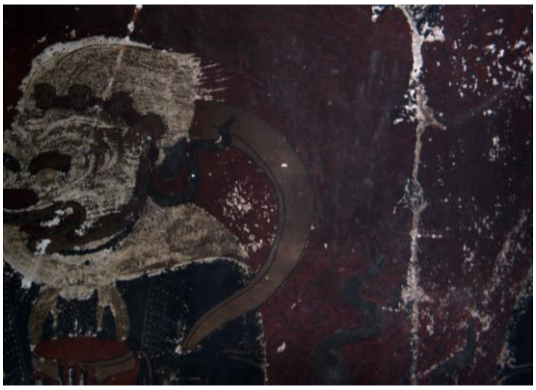
(**d**)

Figure 9. The restoration effects of area 1 without different steps of the proposed method: (a) synthetic true color image; (b) restoration effect without MNF transformation; (c) restoration effect without prior dark channel; (d) restoration effect of the proposed method.

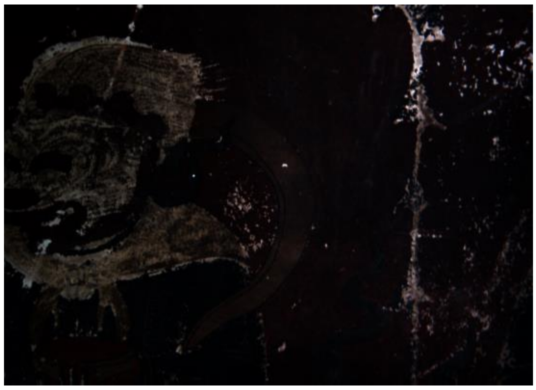
It can be seen from Figure 9 that omitting the MNF transformation resulted in more noise in the image, which affected the effect of sootiness removal. If the dark channel prior sootiness removal was omitted, the image was brighter after restoration; however, the details were not prominent, and the restoration effect of sootiness mural was not significant.

4.4. Comparison with Other Methods

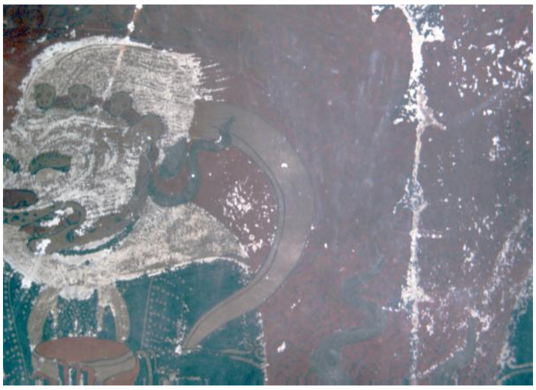
Homomorphic filtering is another common algorithm for image defogging, and Gaussian stretching is a common method for image enhancement. In order to compare their effects with that by the proposed method, the above methods were applied to the true color image synthesized by hyperspectral data in area 1, as shown in Figure 10. Moreover, variance, average gradient, information entropy and gray scale contrast were introduced as objective evaluation indexes, as shown in Table 3. The larger the values of variance, average gradient, information entropy, and gray contrast, the better is the sootiness restoration effect. In addition, according to the no-reference quality assessment method for defogged images proposed by Li et al. [33], the restoration quality of sootiness mural image was objectively evaluated from three aspects: effective edge strength, color restoration ability and structural information. The calculation results are shown in Table 4. Similarly, the larger the values of effective edge intensity, color restoration ability, structure information, and comprehensive evaluation, the better is the sootiness restoration quality.



(**a**)



(**b**)



(**c**)

(**d**)

Figure 10. The restoration effects of area 1 with different methods: (a) synthetic true color image; (b) restoration effect of homomorphic filtering method; (c) restoration effect of Gaussian stretching method; (d) restoration effect of the proposed method.

Table 3. The statistics performance of different methods.

Metric	**True color Image**	**Homomorphic Filtering**	**Gaussian Stretching**	**Proposed Method**
Variance	773.23	265.84	985.04	**1058. 04**
Average gradient	2.59	1.33	2.94	**5.06**
Information entropy	6.44	4.70	6.73	**6.88**
Gray scale contrast	16.41	6.72	20.81	**21.08**

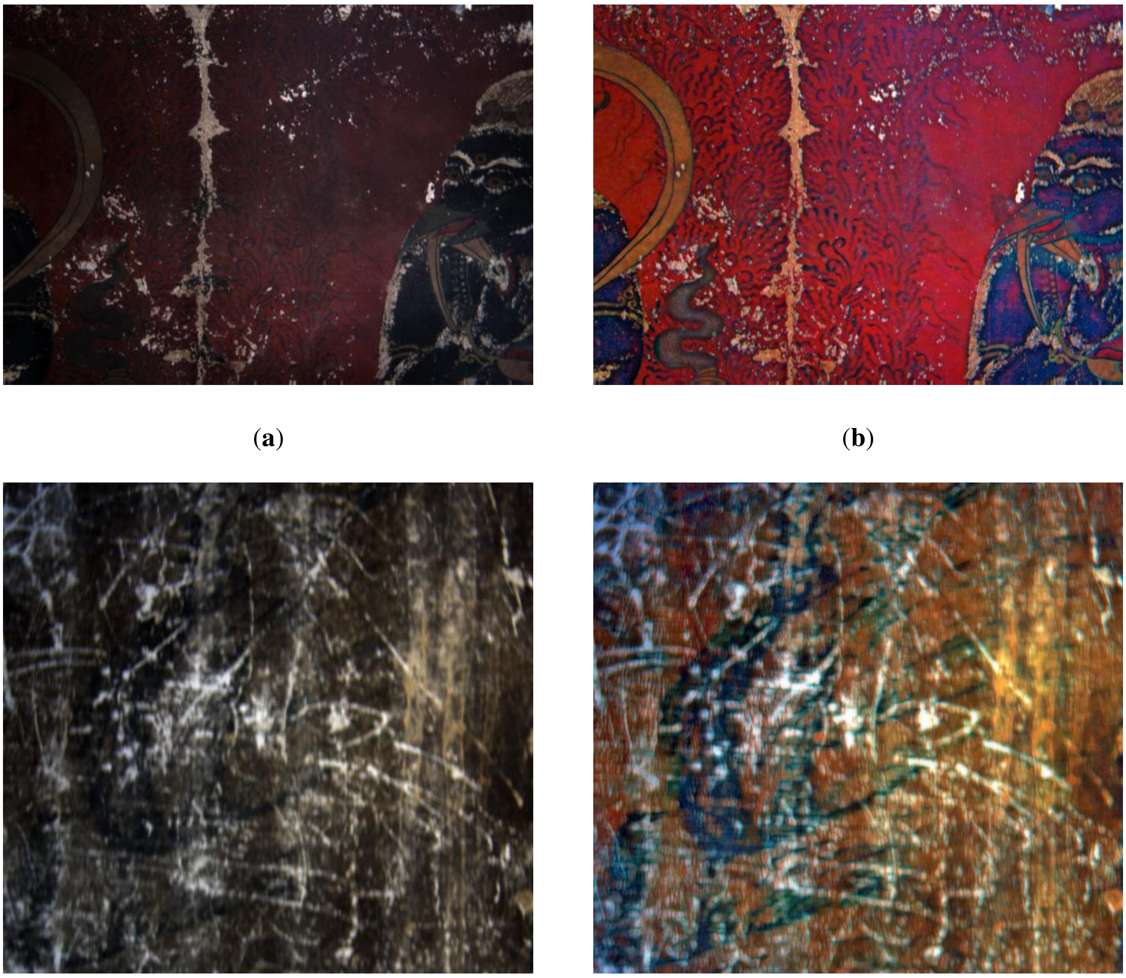
Table 4. The no-reference quality assessment of different methods.

Metric	Homomorphic Filtering	Gaussian Stretching	Proposed Method
Effective edge intensity	**0.74**	0.31	0.41
Color restoration ability	0.19	**0.44**	0.37
Structure information	0.33	0.55	**0.71**
Comprehensive evaluation	0.05	0.07	**0.11**

In terms of visual effects, as shown in Figure 10, the Gaussian stretching algorithms significantly improved the brightness of the image, but the processed image was generally white, the contrast was reduced, and details were lost seriously. The brightness of the image restored by homomorphic filtering algorithm was still dim, and the visual effect was not good. The algorithm in this paper can not only improve the brightness of the sootiness mural image, but also enhance the global contrast and details. In terms of objective quality evaluation, the results in tables 3 and 4 show that the variance, average gradient, information entropy and gray contrast of the proposed method were superior to other algorithms, and the evaluation of comprehensive edges, hue and structure were better too.

4.5. Applicability of Restoration Method Proposed

In order to test the applicability of restoration method proposed, other mural images suffered from sootiness were restored in the same way. The study area 2 of the mural on the same wall of Qutan Temple was restored with the same method and parameters. The effect is shown in Figure 11b. The same approach was performed on an area on the west wall of Guanyin Temple, Heilongmiao Village, Yanqing District, Beijing, China, which was acquired in July 2017. The synthetic true color image is shown in Figure 11c. The patterns on the mural in this area are seriously contaminated by sootiness and cannot be recognized by the naked eye. As shown in Figure 11d, after the restoration, the pattern under the sootiness can be more clearly identified.



(**a**) (**b**)

(**c**) (**d**)

Figure 11. The restoration results of sootiness murals in other study areas: (a) synthetic true color image of area 2 of Qutan Temple; (b) restoration results of area 2 of Qutan Temple; (c) synthetic true color image of Guanyin Temple; (d) restoration results of sootiness mural of Guanyin Temple.

In addition, other six images were restored and mosaicked to one image covering the first Buddha in the left of the mural on the same wall of Qutan Temple, as shown in Figure 12. Therefore, the restoration method of sootiness mural in this paper can achieve the removal of sootiness in different murals and the restoration of large-scale sootiness murals.

Figure 12. The restoration and mosaic result of the left Buddha of Qutan Temple.

4.6. Inpainting of the Paint Losses in the Background

Finally, in order to further improve the visual quality of the mural restoration, the paint losses in the background was inpainted. After the experiment, the image after the preliminary sootiness removal step was selected, the paint losses in the image was inpainted by Criminisi algorithm, and the restoration of sootiness mural by Retinex by Bilateral Filter was performed on the inpainted image. The final restoration effect is shown in the Figure 13.

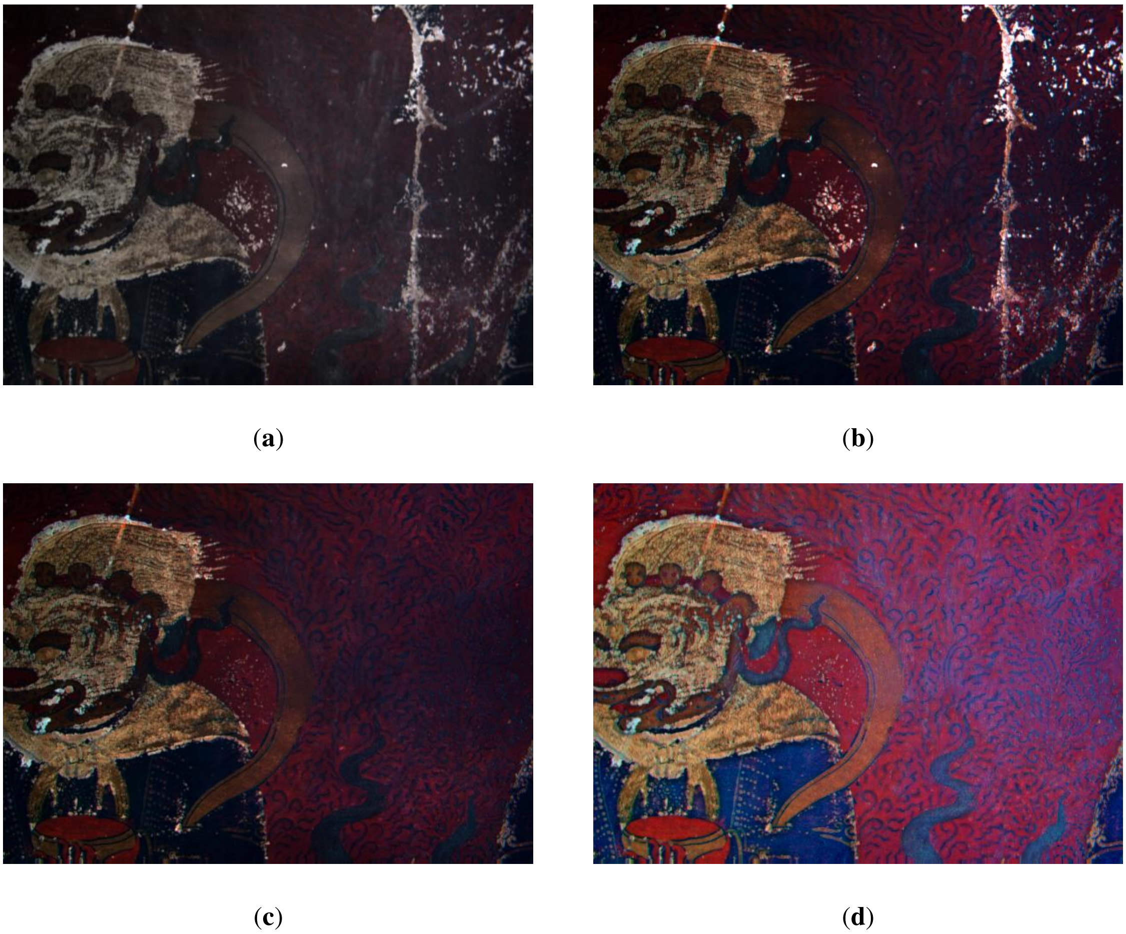


Figure 13. The final restoration result of area 1: (a) synthetic true color image; (b) result of preliminary sootiness removal; (c) result of paint losses inpainting; (d) final restoration result.

In terms of visual effects, after sootiness restoration and paint losses inpainting, the mural image was more enjoyable and attractive, and revealed the original appearance of mural to a large extent.

5. Conclusions

It is an arduous task in the protection of cultural relics to remove sootiness from murals. The objective of this study is to develop a new method to virtually restore sootiness mural images using hyperspectral imaging technology. By using the advantages of near-infrared bands, the related defogging methods, dark channel prior and Retinex by bilateral filter, were combined to reveal the mural patterns blurred by sootiness contamination. The approach was carried out on several sootiness mural images. The readability and artistic expression of the murals were increased effectively. The experimental results show that the restoration method can remove most of the sootiness, highlight the global contrast and detail information, make the image brighter, the lines clearer and the pattern more attractive. Good results have also been achieved in the objective evaluation of variance, average gradient, information entropy, gray contrast and comprehensive evaluation. Although, the block histogram matching can make the clothes clearer and color more realistic, the details processing of clothes with complex patterns and dense paint losses still need to be improved. It is necessary to further study the radiometric transmission model which is more suitable for mural sootiness, so as to realize the restoration of sootiness mural more effectively.

Abbreviations

HSV: Hue, saturation, value; MNF: minimum noise fraction rotation; PCI: Pseudo color image; TCI: True color image; SMI: Sootiness mural image; V: Value; RGB: Red, green, blue.

Acknowledgements

The research project Protection of Murals in Qutan Temple was initiated and organized by the Dunhuang Academy. The Dunhuang Academy have made their equipment, expertise and research time available for the benefit of this research. The author would like to thank the staff of Dunhuang Academy and Qutan Temple.

Authors' contributions

Conceptualization: CN, LSQ and HML. Data curation: CN and GZH. Methodology: CN, LSQ and HML. Validation: CN, LSQ, HML and AS. Formal analysis: CN, LSQ, HML and AS. Resources: WWF, HML, LSQ and DYQ. Writing–original draft: CN, LSQ, HML and AS. Writing–review: all authors. The paper was approved by all authors. All authors read and approved the final manuscript.

Funding

This research was funded by the Research Fund of the National Key R&D Program of China (No. 2019YFC1520800), the Great Wall Scholars Training Program Project of Beijing Municipality Universities (CIT&TCD20180322), and Beijing Postdoctoral Research Foundation.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Author details

1 Beijing University of Civil Engineering and Architecture, No.15 Yongyuan Road, Daxing District, Beijing 102616, China.
2 Beijing Key Laboratory for Architectural Heritage Fine Reconstruction & Health Monitoring, No.15 Yongyuan Road,

Daxing District, Beijing 102616, China. 3 The Dunhuang Academy, Dunhuang 736200, China. 4 Shanxi Provincial Institute of Archaeology, Taiyuan 030000, China. 5 Ryerson university, 350 Victoria Street, Toronto ON M5B 2K3, Canada.

References

1. Wang WF, Ma ZF, Li ZX, et al. Consolidating of detached murals through grouting techniques. Sciences of Conservation and Archaeology. 2006;18(1):52–59. (in Chinese)
2. Li Y, Wang FP, Fu XY, et al. Analysis of the pigments for smoked mural by confocal micro-Raman spectroscopy. Journal of Raman Spectroscopy. 2017;48(11):1479-1486.
3. Tseking, Lhaba T. Protective Cleaning of the Smudged Mt Wutai Mural in the Kelsang Phodang of Norbulingka. Hunan Provincial Museum. 2017(00):637–642. (in Chinese)
4. Wang H. Inpainting of Potala Palace murals based on sparse representation. In: 2015 8th International Conference on Biomedical Engineering and Informatics (BMEI). IEEE, 2015. p. 737–741.
5. Li CY, Wang HQ, Wu M, et al. Automatic recognition and virtual restoration of mud spot disease of Tang dynasty tomb murals image. Comput. Eng. Appl. 2016;52:233–236. (in Chinese)
6. Jaidilert S, Farooque G. Crack Detection and Images Inpainting Method for Thai Mural Painting Images. In: 2018 IEEE 3rd International Conference on Image, Vision and Computing (ICIVC). IEEE, 2018. p. 143–148.
7. Purkait P, Ghorai M, Samanta S, et al. A Patch-Based Constrained Inpainting for Damaged Mural Images. In: Digital Hampi: Preserving Indian Cultural Heritage. Springer, Singapore, 2017. p. 205–223.
8. Shen JN, Wang HQ, Wu M, et al. Tang Dynasty Tomb Murals Inpainting Algorithm of MCA Decomposition. J Front Comput Sci Technol. 2017;11:1826–1836. (in Chinese)
9. Wang Z, Wang HQ, Wu M, et al. Research on automated virtual restoration of the Ming Dynasty murals in a Guanyin Temple in Xinjin. Sciences of Conservation and Archaeology. 2018;30(03):109–113. (in Chinese)
10. Cao JF, Zhang ZB, Zhao AD, et al. Ancient mural restoration based on a modified generative adversarial network. Heritage Science. 2020;8(1):7.
11. Wang M, Zhou SD, Liu ZH, et al. Research Methods on Cloud and Fog Removal Processing of Remote Sensing Images. Research and Exploration in Laboratory. 2011;30(02):34–37. (in Chinese)
12. Zhao CL, Dong JW, Xu B, et al. Research on Finger-image Enhancement Algorithm Based on Fusion Histogram Equalization and Homomorphic Filtering. Journal of Harbin University of Science and Technology. 2019;24(06):93–97. (in Chinese)
13. Tao L, Asari V. Modified luminance based MSR for fast and efficient image enhancement. In: 32nd Applied Imagery Pattern Recognition Workshop, 2003. Proceedings. IEEE, 2003. p. 174–179.
14. Elad M. Retinex by two bilateral filters. In: International Conference on Scale-Space Theories in Computer Vision. Springer, Berlin, Heidelberg, 2005. p. 217–229.
15. Tian HJ, Cai MP, Guan T, et al. Low-light Image Enhancement Method Using Retinex Method Based on YCbCr Color Space. Acta Photonica Sinica. 2020;49(2):173–184. (in Chinese)

16. He K, Sun J, Tang X. Single image haze removal using dark channel prior. IEEE transactions on pattern analysis and machine intelligence. 2010;33(12):2341–2353.
17. Yue BX, Liu KL, Wang ZY, et al. Accelerated haze removal for a single image by dark channel prior. Frontiers of Information Technology & Electronic Engineering. 2019;20(8):1109-1118.
18. Mansfield JR, Attas M, Majzels C, et al. Near infrared spectroscopic reflectance imaging: a new tool in art conservation. Vibrational Spectroscopy. 2002;28(1):59–66.
19. Zhou PP, Hou ML, Lv SQ, et al. Virtual Restoration of Stained Chinese Paintings Using Patch-Based Color Constrained Poisson Editing with Selected Hyperspectral Feature Bands. Remote Sensing. 2019;11(11):1384.
20. Han D, Ma L, Ma S, et al. The digital restoration of painted patterns on the No. 2 Qin bronze chariot based on hyperspectral imaging. Archaeometry. 2020;62(1):200–212.
21. Kim SJ, Deng F, Brown MS. Visual enhancement of old documents with hyperspectral imaging. Pattern Recognit. 2011;44(7):1461–1469.
22. Wu TX, Li GH, Yang ZH, et al. Shortwave Infrared Imaging Spectroscopy for Analysis of Ancient Paintings. Applied spectroscopy. 2017;71(5):977–987.
23. Guo XL, Zhang LF, Wu TX, et al. Hidden information extraction from the ancient painting using hyperspectral imaging technology. Journal of Image and Graphics. 2017;22(10):1428–1435. (in Chinese)
24. Peng JY, Yu K, Wang J, et al. Mining painted cultural relic patterns based on principal component images selection and image fusion of hyperspectral images. Journal of Cultural Heritage. 2019;36:32–39.
25. Tonazzini A, Salerno E, Abdel-Salam ZA, et al. Analytical and mathematical methods for revealing hidden details in ancient manuscripts and paintings: A review. Journal of advanced research. 2019;17:31–42.
26. GB/T 30237-2013, Ancient wall painting deterioration and legends.
27. Wang XZ. The Architectural Objects of Ming and Qing Dynasties in Qutan Temple and The Architectural Colored Drawings in Mural Paintings. Art Magazine. 2019;11:118. (in Chinese)
28. Green AA, Berman M, Switzer P, et al. A transformation for ordering multispectral data in terms of image quality with implications for noise removal. IEEE Transactions on geoscience and remote sensing. 1998;26(1):65–74.
29. Narasimhan SG, Nayar SK. Vision and the atmosphere. International journal of computer vision. 2002;48(3):233–254.
30. Oakley JP, Satherley BL. Improving image quality in poor visibility conditions using a physical model for contrast degradation. IEEE transactions on image processing. 1998;7(2):167–179.
31. Tomasi C, Manduchi R. Bilateral filtering for gray and color images. In: Sixth international conference on computer vision (IEEE Cat. No. 98CH36271). IEEE, 1998. p. 839–846.
32. Dong JW, Zhao CL, Hai B. Research on Image De-fog Algorithm Based on Fusion Homomorphic Filtering and Wavelet Transform. Journal of Harbin University of Science & Technology. 2019;24(01):66-70. (in Chinese)
33. Li DP, Yu J, Xiao CB. No-reference quality assessment method for defogged images. Journal of Image and Graphics. 2011;16(09):1753–1757. (in Chinese)

Figures

Figure 1

Sootiness legend of mural.

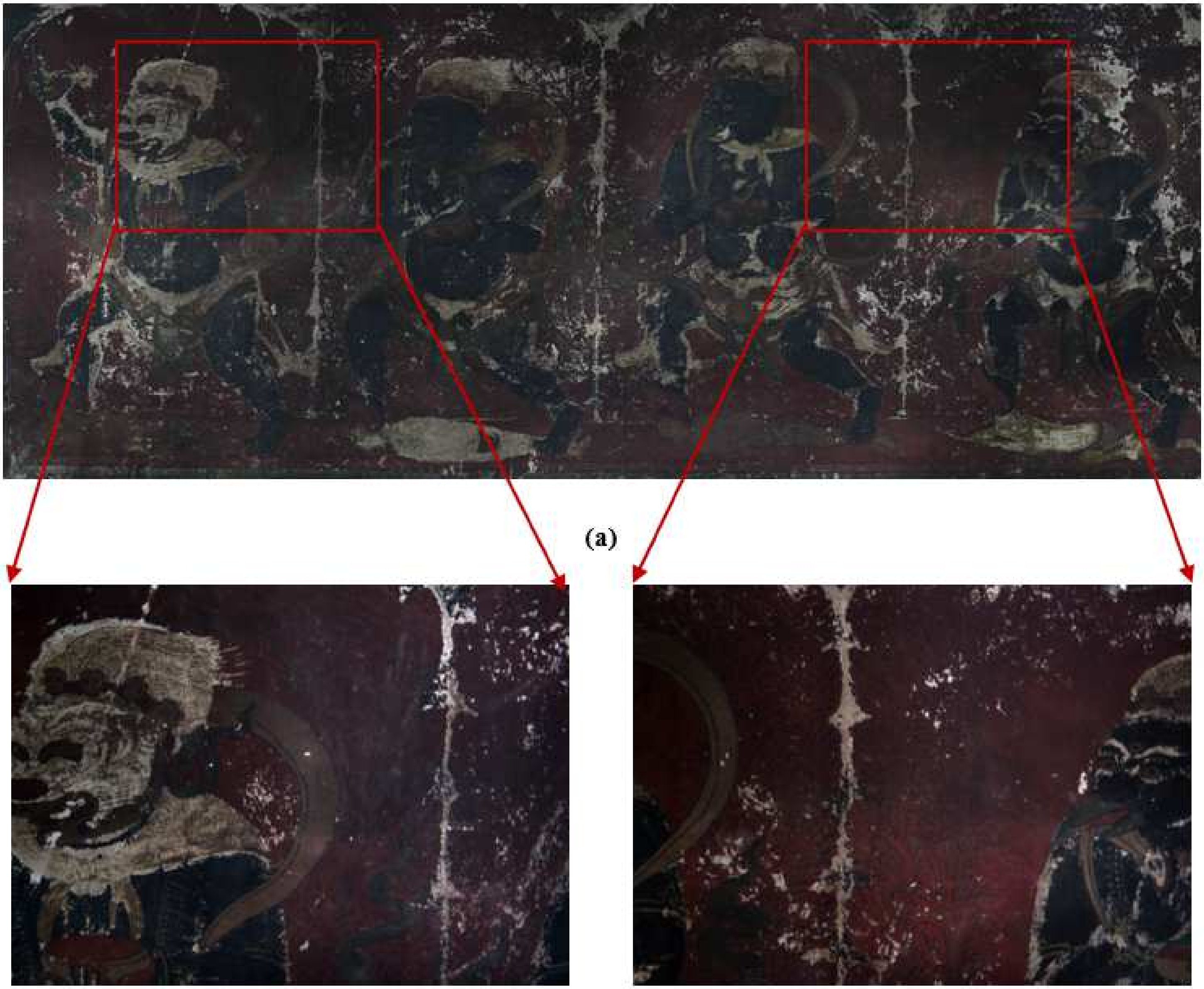


Figure 2

The image of the mural and the two study areas: (a) complete image of the mural; (b) image of the first study area; (c) image of the second study area.

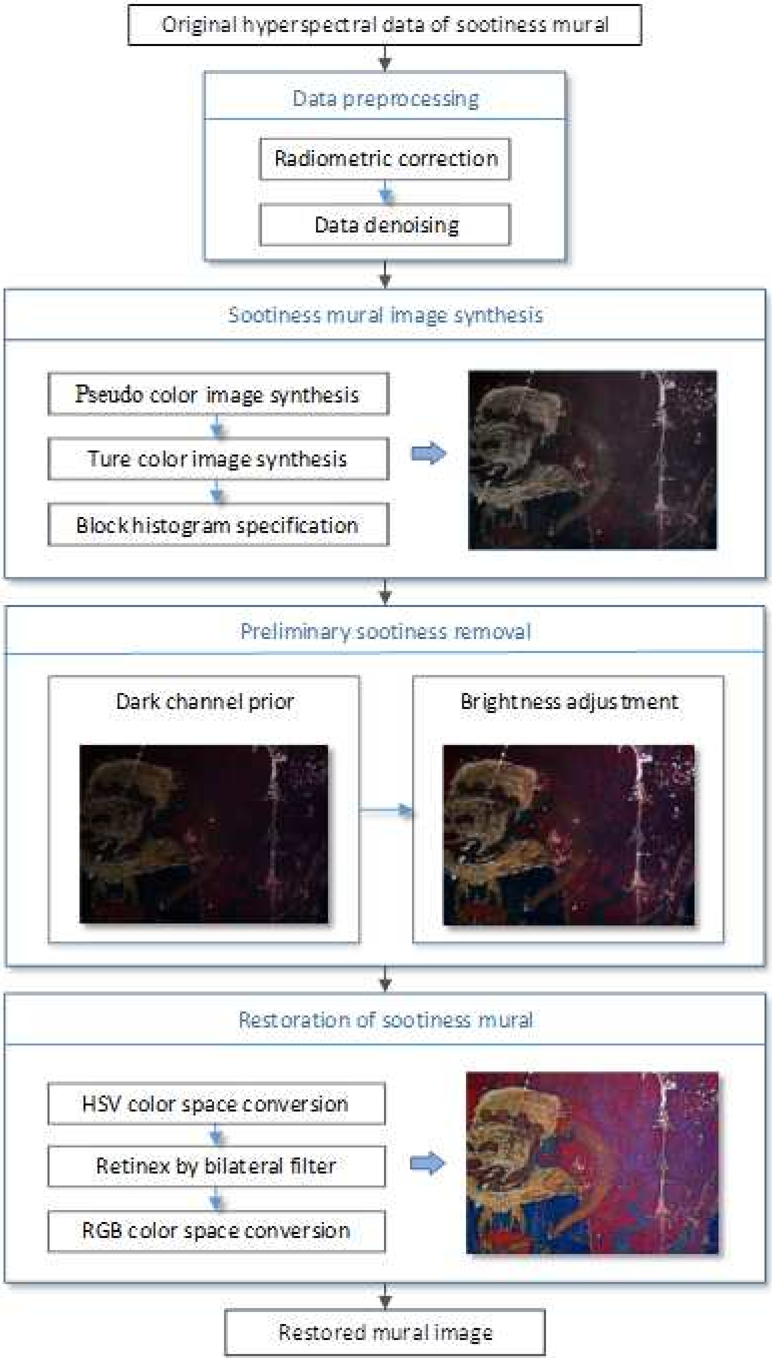


Figure 3

The overall workflow of the proposed method.

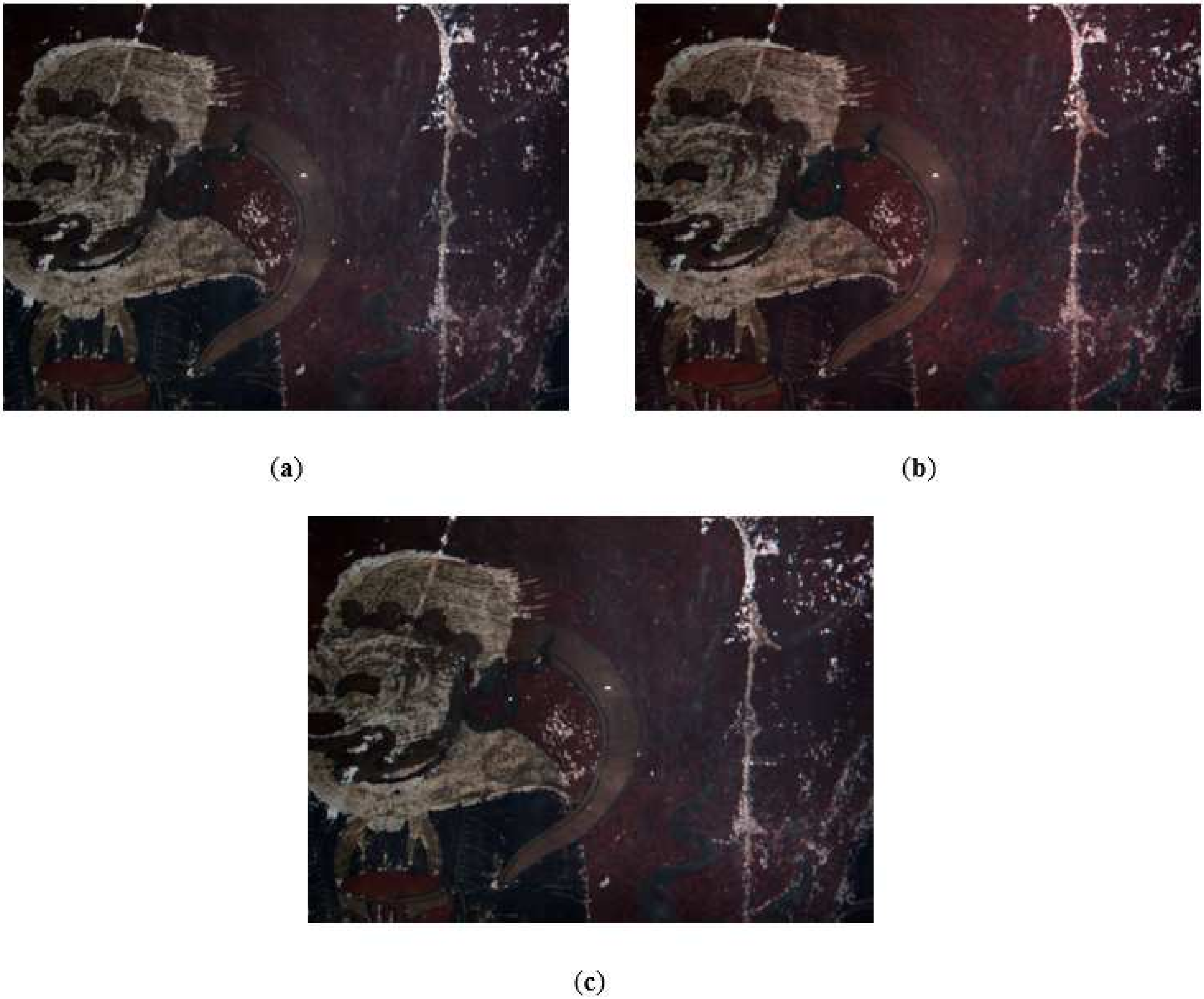


Figure 4

The synthetic hyperspectral image of area 1: (a) true color image (TCI); (b) pseudo color image (PCI); (c) sootiness mural image (SMI).

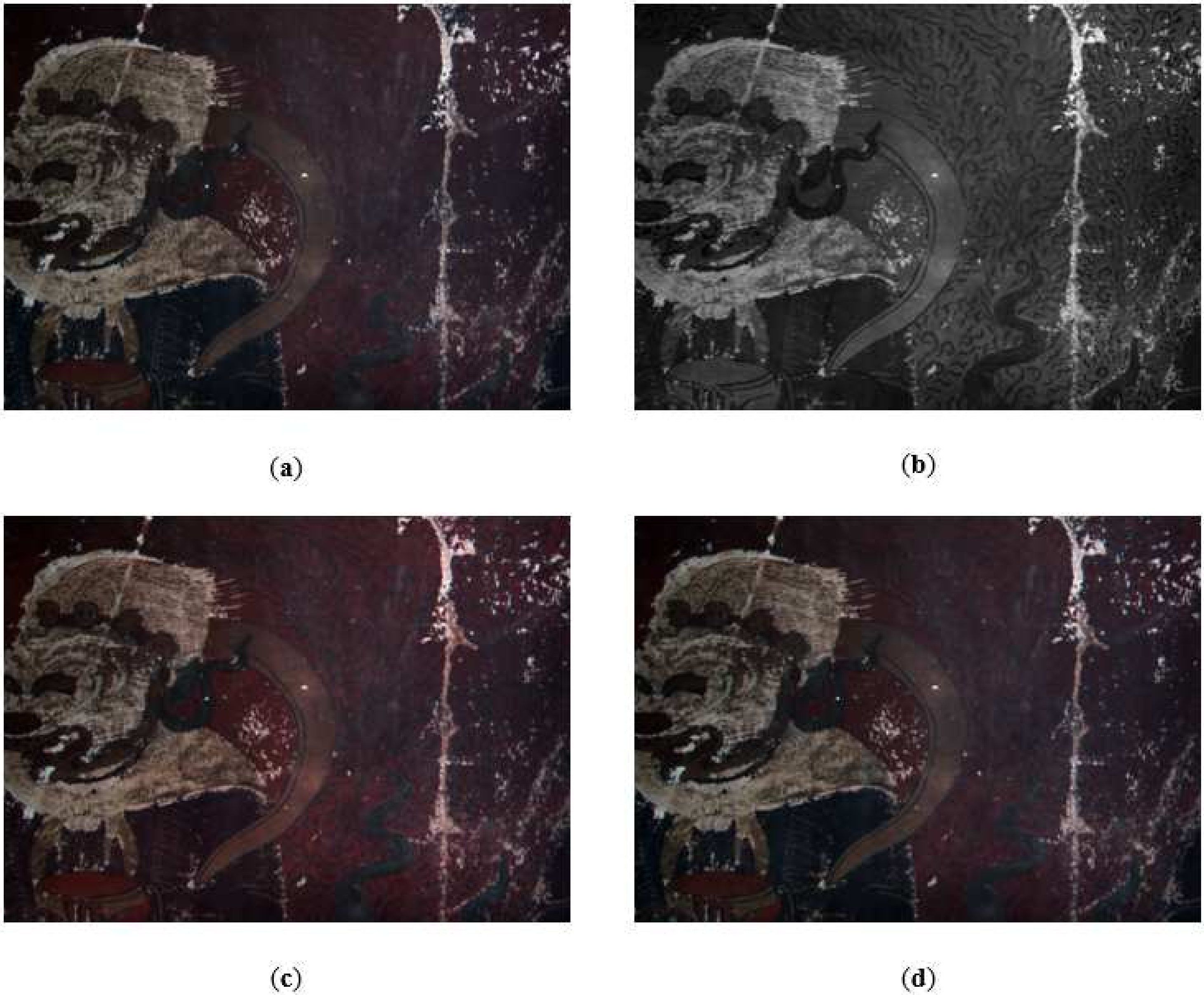


Figure 5

The synthetic sootiness mural image of area 1: (a) synthetic true color image; (b) near-infrared band image; (c) synthetic pseudo color image; (d) sootiness mural image after block histogram matching.

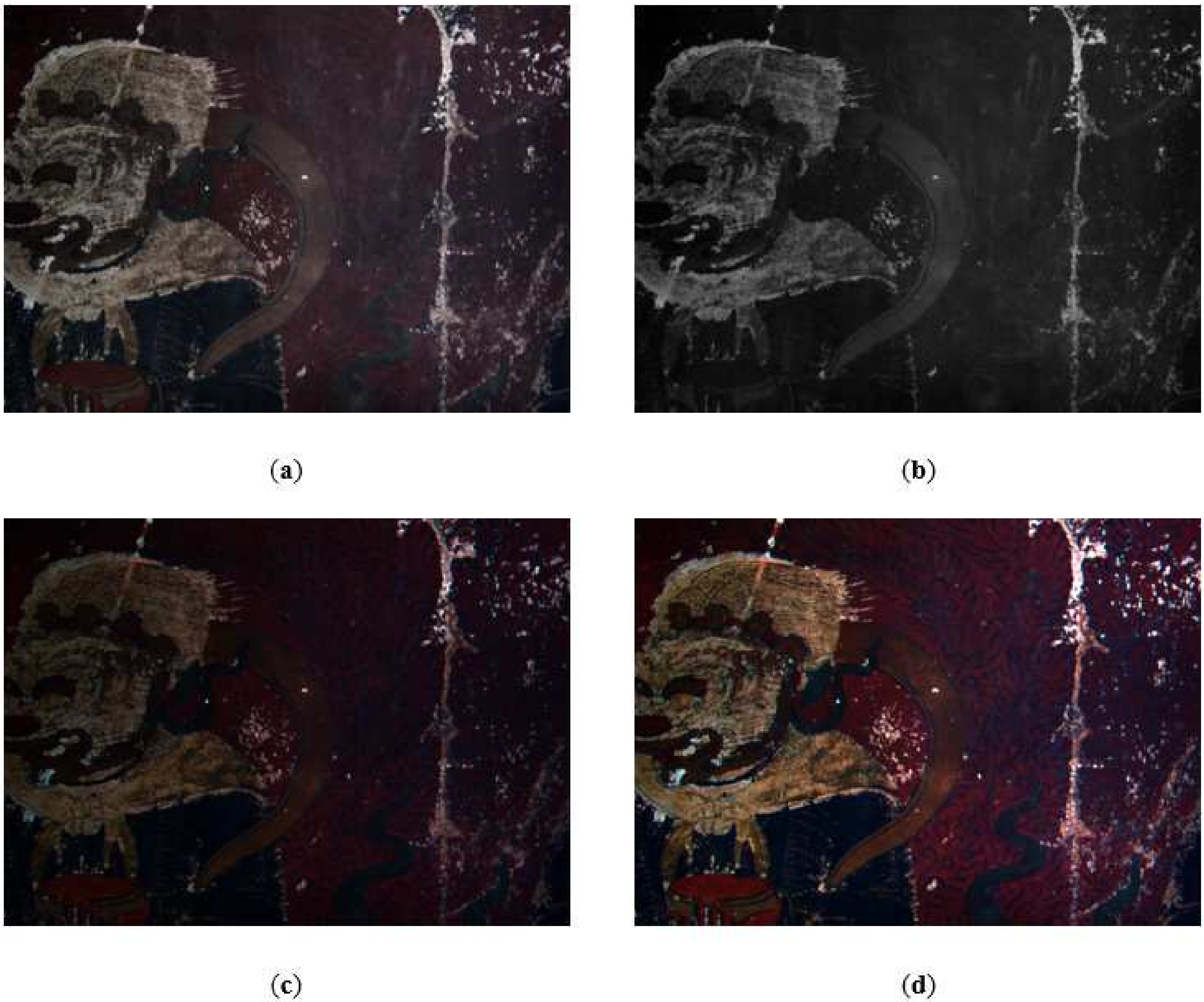


Figure 6

The preliminary sootiness removal results of area 1: (a) synthetic true color image; (b) dark channel image; (c) result of dark channel priori sootiness removal; (d) result of brightness adjustment.

(a) (b)

Figure 7

The restoration result of area 1: (a) synthetic true color image; (b) restoration result.

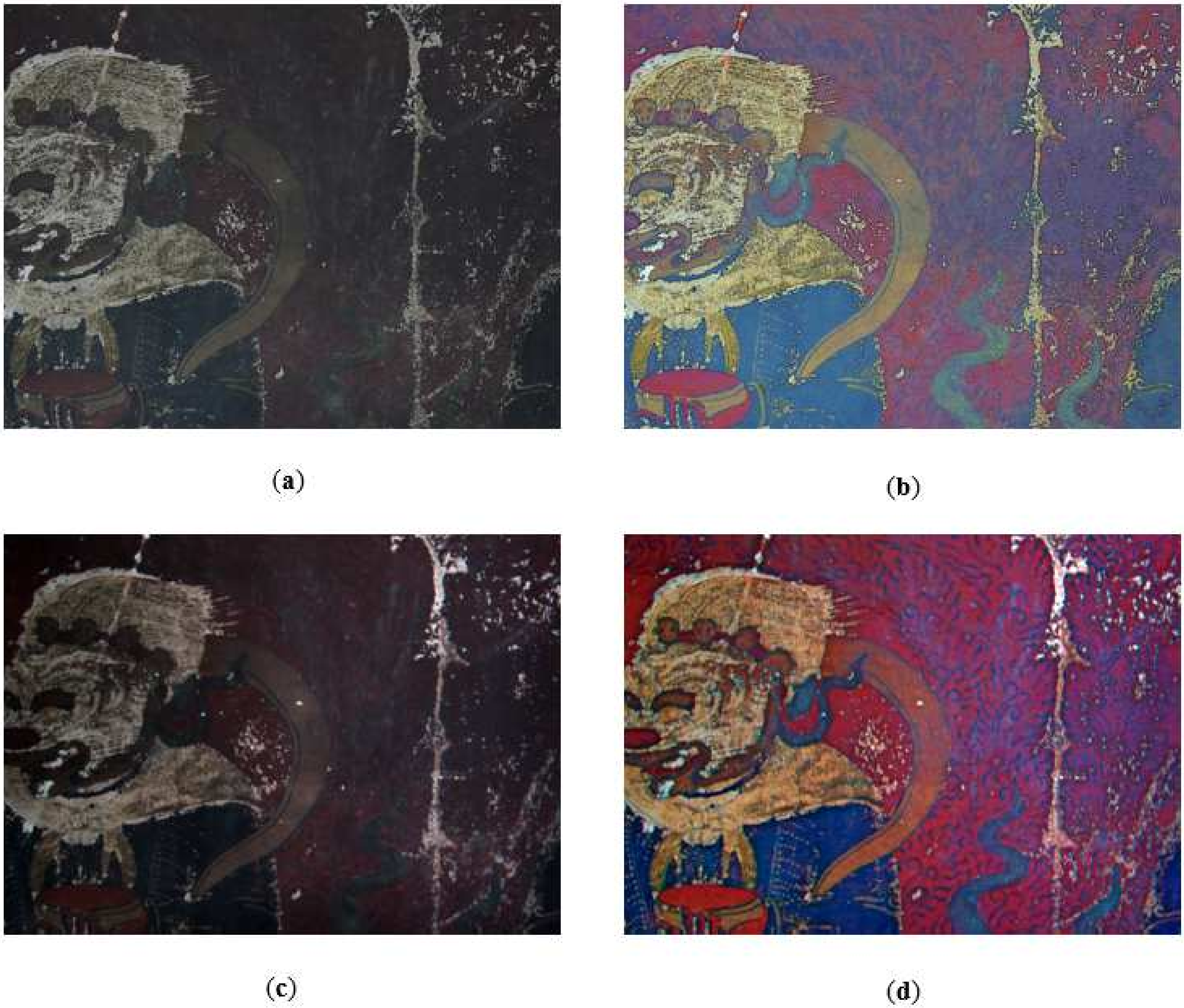


Figure 8

The restoration effects of digital photo and hyperspectral synthetic image of area 1: (a) digital photo; (b) restoration effect of digital photo; (c) hyperspectral synthetic image; (d) restoration effect of hyperspectral synthetic image.

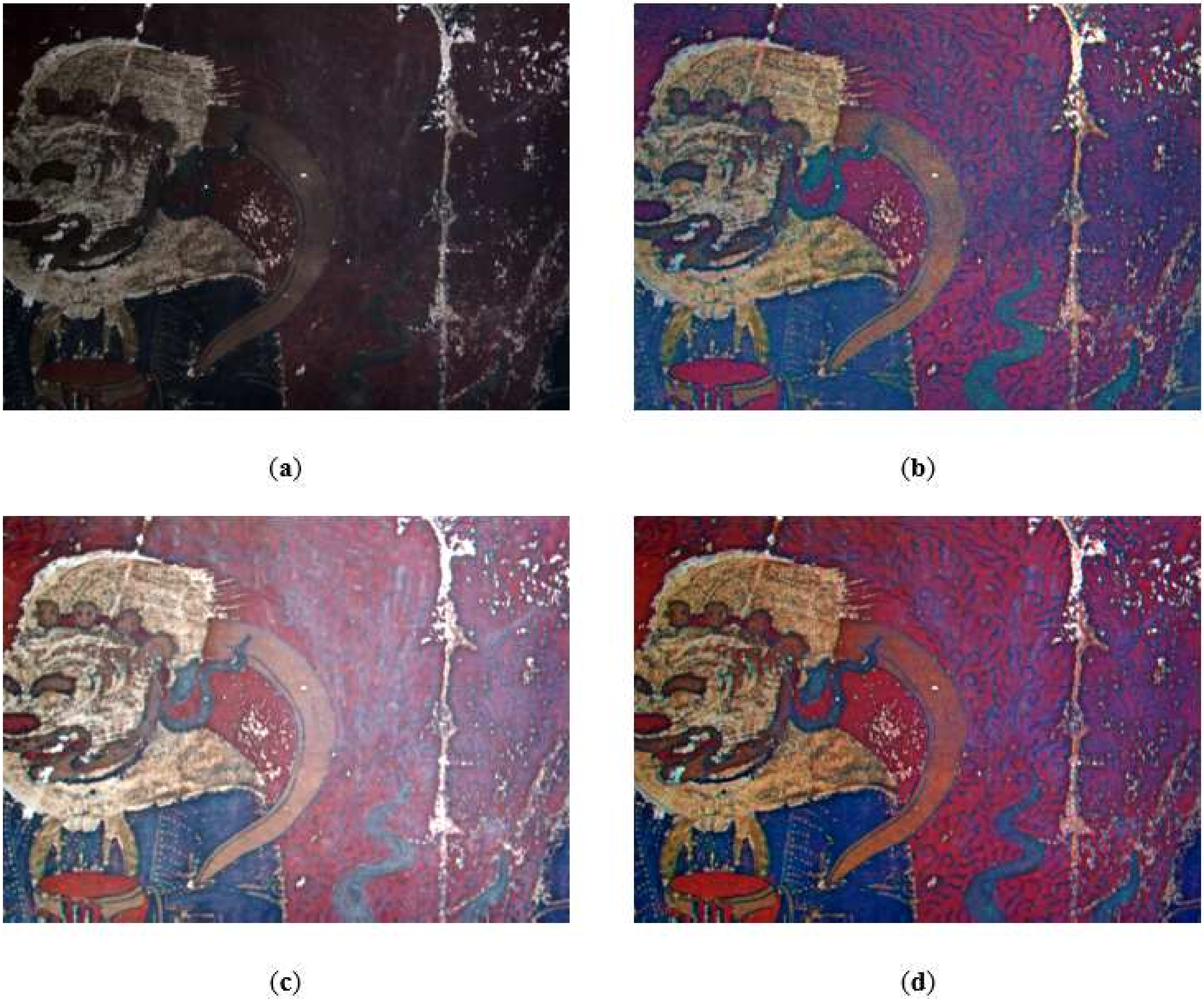


Figure 9

The restoration effects of area 1 without different steps of the proposed method: (a) synthetic true color image; (b) restoration effect without MNF transformation; (c) restoration effect without prior dark channel; (d) restoration effect of the proposed method.

(a)

(b)

(c)

(d)

Figure 10

The restoration effects of area 1 with different methods: (a) synthetic true color image; (b) restoration effect of homomorphic filtering method; (c) restoration effect of Gaussian stretching method; (d) restoration effect of the proposed method.

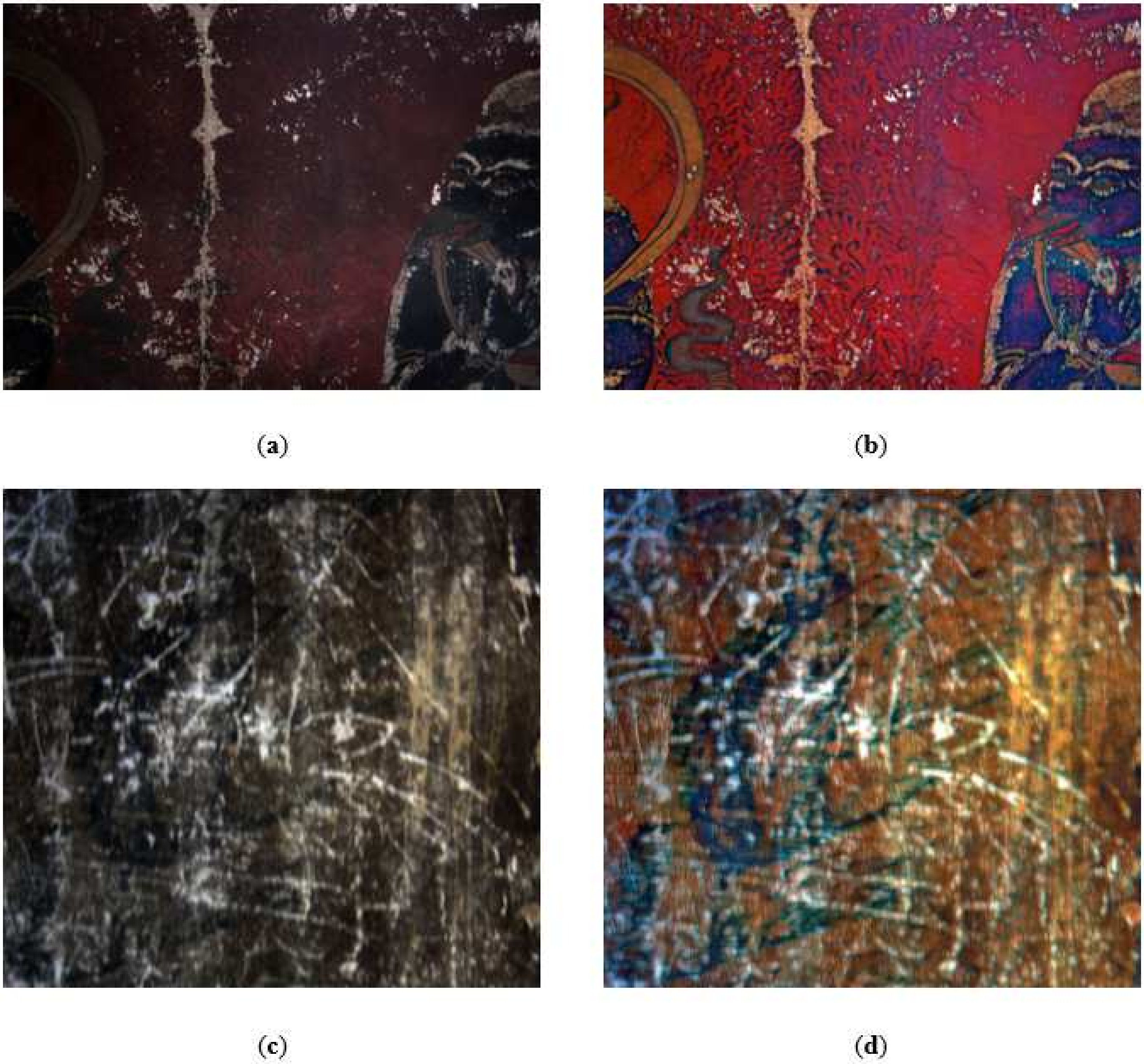


Figure 11

The restoration results of sootiness murals in other study areas: (a) synthetic true color image of area 2 of Qutan Temple; (b) restoration results of area 2 of Qutan Temple; (c) synthetic true color image of Guanyin Temple; (d) restoration results of sootiness mural of Guanyin Temple.

Figure 12

The restoration and mosaic result of the left Buddha of Qutan Temple.

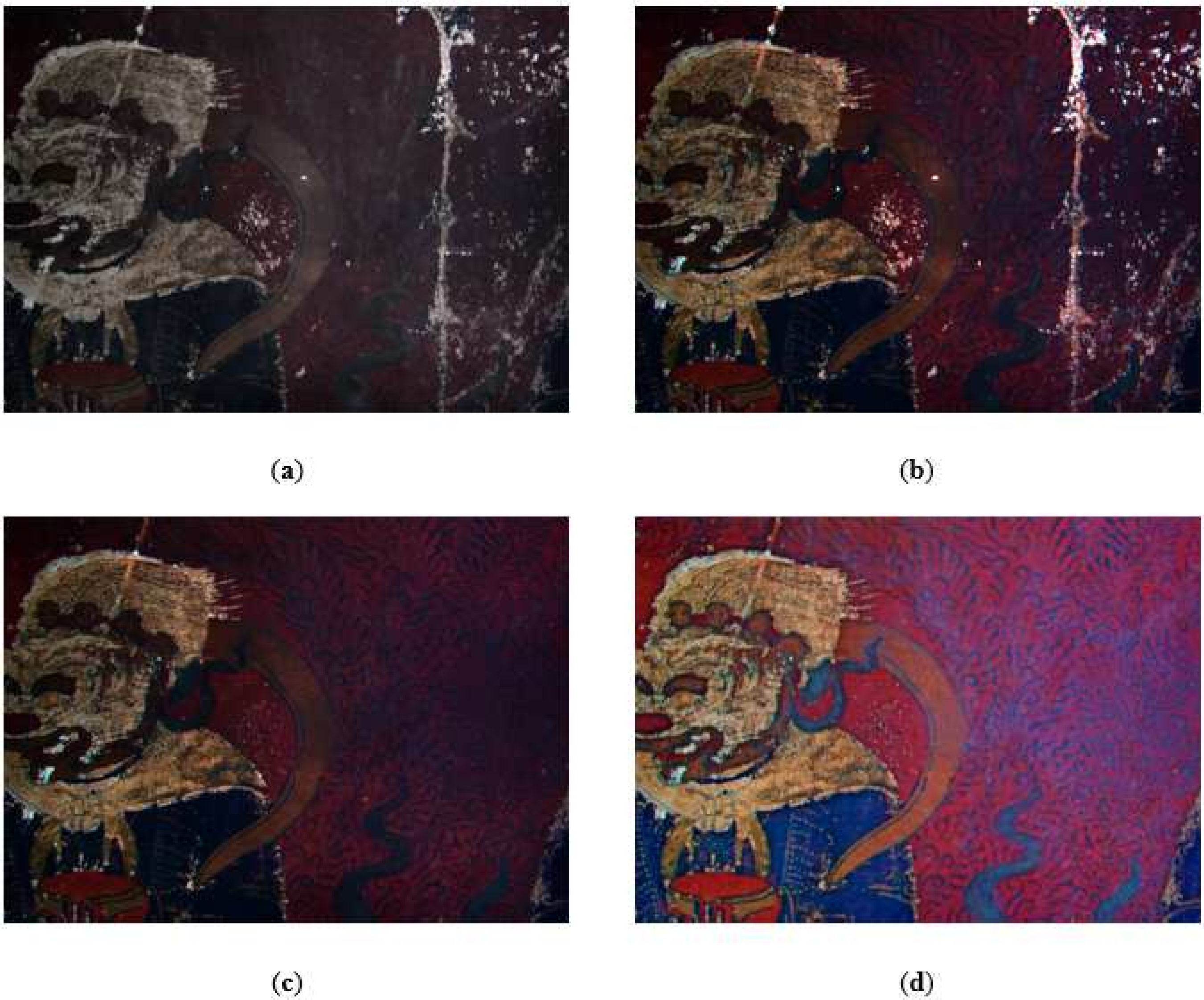


Figure 13

The final restoration result of area 1: (a) synthetic true color image; (b) result of preliminary sootiness removal; (c) result of paint losses inpainting; (d) final restoration result.