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Research Article

Artificial Intelligence-Based color Reconstruction of Mogao Grottoes Murals Using Computer Vision Techniques

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Abstract:

The Mogao Grottoes murals have deteriorated over centuries due to environmental exposure, pigment degradation, and natural ageing, making cultural heritage preservation difficult. AI and computer vision can identify, classify, and reconstruct faded pigments, revolutionizing color restoration. This reconstructs faded mural sections using deep learning, image processing, and pigment data implemented through TensorFlow, PyTorch and OpenCV. The study uses high-resolution Digital Dunhuang database images of Mogao Grottoes murals and 50 pigments categorized by color, stability, and chemical composition. CNNs and deep learning-based color mapping algorithms detect fading and suggest color restorations of pigments. AI reconstructions along with history accuracy through expert evaluations and pigment records. Artificial intelligence-driven mural conservation detects faded pigments, precisely reconstructs missing sections, and matches restored colors to historical authenticity, improving accuracy, efficiency, and scalability. Scientifically, AI-based digital heritage conservation outperforms manual restoration. AI preserves and faithfully reconstructs cultural heritage sites using historical artworks using global digital pigment database and deep learning-driven restoration models. The first reproducible and scientific model (CNN, GAN and deep learning-based color mapping algorithms) using AI-based color restoration and historical pigment analysis in Mogao Grottoes murals was created.

1. Introduction

The Caves of the Thousand Buddhas, or Mogao Grottoes, are one of ancient China's greatest cultural and historical treasures. They combine Buddhist art, religious devotion, and cross-cultural The Silk Road caves in Dunhuang, Gansu Province, contain dynasty-era murals, sculptures, and manuscripts. These cave murals depict Chinese history, religion, and art using intricate techniques and natural pigments [1]. Despite their cultural and academic value, the murals have deteriorated over centuries due to natural ageing, environmental exposure, and human interference. These cultural heritage sites are harder to preserve and restore due to paint degradation, which has caused fading, discoloration, and color loss. Paint degradation has caused significant fading, discoloration, and even color loss, making it difficult for art historians, archaeologists, and conservators to preserve these valuable works [2].

Culture, art history, archaeology, and digital humanities research require mural color preservation. The original mural colors show ancient craftsmen's artistic choices, symbolic meanings, and material technologies, helping researchers understand their aesthetic and religious contexts. Public education and museum exhibitions require accurate color preservation to fully experience murals. Manual retouching, digital archiving, and spectral imaging preserved Mogao Grottoes murals. These restoration methods rarely reconstruct pigments accurately. However, spectral imaging is better at pigment identification and color reconstruction, even in complex restoration processes. Manual restoration is subjective and time-consuming, affecting color reproduction. Digital imaging preserves pigments but reconstructing their chromatic values after centuries of chemical change is difficult. For scientific accuracy and artistic integrity, mural restoration requires technology [3-5].

1.1. Problem statement

Mural restoration research is limited by the inability to precisely reconstruct faded pigments while preserving historical accuracy and artistic integrity. Although spectral imaging can identify pigment compositions, it cannot recreate ancient murals' complex tonal variations and fading patterns. Traditional restoration relies on subjective expert judgement. Large-scale conservation projects cannot use inefficient and unscalable traditional restoration methods. No standard digital pigment database for automated restoration is another drawback. AI models for Chinese Buddhist murals are rare because most art restoration AI applications target Western works. Image clarity is improved by most AI-based restoration methods, but historical pigment analysis, spectral imaging, and expert validation are missing [6,7].

Deep learning, computer vision, and historical pigment analysis create an AI-driven Mogao Grottoes mural color restoration framework. To accurately reconstruct faded pigments and preserve mural art and history [8]. Restoration methods are improved by CNNs, GANs, and Transformer-based vision models trained on large historical pigment and mural datasets. This study proposes a data-driven mural restoration method that analyses pigment spectral properties, detects degradation patterns, and predicts faded section hues to replace manual methods. This research also aims to standardize a digital pigment database with historically accurate pigment compositions for AI-driven restoration models for consistency and reproducibility. Conservators and researchers can use AI to restore mural sections and possibly other heritage sites [9,10].

This AI project reconstructed faded murals using spectral imaging, historical pigment data, and deep learning. After editing high-resolution digital Mogao Grottoes mural pictures, spectral reflectance and chemical properties classify pigments. AI-driven pattern recognition and color prediction technologies restore fading hues to historical accuracy. Expert art historians and conservators check AI-generated colors against history. Scientifically rigorous and scalable digital heritage conservation is possible with computational accuracy and expert knowledge.

This study shows how AI can automate and improve mural restoration while preserving culture. Tradition restoration methods fail, and the study proposes a practical, scalable, and scientifically validated solution using advanced computational methods. Archaeologists, conservators, museum professionals, and digital heritage researchers can now preserve and reconstruct cultural artefacts with confidence. A standardised digital pigment database and AI-driven color reconstruction techniques will preserve historical murals' vibrancy and authenticity for future generations.

2. Literature Review

2.1 Color degradation and restoration in Mogao Grottoes murals

The UNESCO World Heritage Mogao Grottoes' Buddhist murals reflect different dynasties' artistic styles, religious themes, and cultural influences [11]. These murals were carefully layered with mineral-based pigments and organic colorants for depth, contrast, and luminosity. Although these pigments are durable, environmental exposure, natural ageing, and chemical reactions with surrounding materials have faded, oxidised, and surface-eroded murals [9]. Due to chromatic integrity loss, historians and conservators have struggled to reconstruct these murals' original artistic vision because many pigment compositions have changed irreversibly. Because pigments like cinnabar, which turns black when oxidised, and azurite, which degrades into malachite, mural elements' colors must be predicted and restored using advanced computational methods [12].

Manual retouching, digital archiving, and spectral imaging identify pigment compositions but cannot recreate original colors. Due to subjective and expert manual retouching, artists' restored works vary. Spectral imaging shows pigment compositions but cannot restore chemically faded colors from centuries ago [13]. These challenges require an AI-driven restoration framework that can objectively analyse pigment degradation patterns, predict original hues from historical data, and reconstruct murals more accurately and efficiently. Deep learning and computer vision can detect pigment degradation patterns in large historical mural datasets and create scientifically validated color reconstructions that match the original artwork [14,15].

2.2 AI-Powered Mural Restoration Enhances Conservation

Artificial intelligence can automate and improve cultural heritage restoration color reconstruction, especially when historical records and pigment compositions are incomplete or unreliable [16,17]. AI-based restoration uses CNNs, GANs, and

Transformer-based vision architectures to process high-resolution mural images, identify pigment degradation patterns, and reconstruct color maps that match the murals' historical aesthetic. CNNs excel at feature extraction, allowing AI models to identify degraded areas, analyse pigment composition variations, and classify mural elements by spectral characteristics. Adversarial training with GANs accurately predicts colors, ensuring restored sections match historical pigment compositions and blend with surrounding artwork. Transformer-based vision models analyse multilevel spectral data to improve mural pigment contextual understanding and ensure accurate color reconstruction [18,19]. Using massive mural and spectral imaging datasets, AI-driven predictions replace time-consuming and subjective manual color restoration. They use large datasets of high-resolution Mogao Grottoes mural scans to learn from well-preserved sections and apply it to degraded areas. Iterative learning improves AI predictions, reconstructing pigments and reducing artificial hues. AI-powered mural conservation ensures color consistency across mural sections and heritage sites with large-scale, reproducible, and scientifically validated restoration [20,21].

2.3 AI Mural Reconstruction: Spectral Analysis and Digital Restoration

Machine learning algorithms must analyse spectral data, detect pigment degradation patterns, and predict missing colors for AI-driven mural restoration. Matching faded sections to their original colors is difficult because historical pigments degrade in complex and unpredictable ways. Multispectral and hyperspectral imaging help AI models identify pigment compositions and degradation patterns by providing detailed spectral reflectance data across multiple wavelengths. Using pigment spectral signatures, AI algorithms can recreate mural colors [21,22].

This AI-based restoration framework integrates spectral imaging, deep learning-based pattern recognition, and automated color mapping in multiple steps. Noise reduction and contrast enhancement clean high-resolution mural images for pigment analysis. Next, CNNs classify degraded sections, extract pigment features, and find pigment transformation patterns. GANs then generate multiple restorations and choose the most historically accurate using spectral data to improve color predictions. Transformer-based models analyse mural elements' spatial and contextual relationships for accurate color reconstruction and composition. Using large datasets of historically documented pigments and mural compositions, the AI system restores mural sections quickly and accurately. AI-based digital restoration tools help conservators preserve murals at risk of environmental and chemical deterioration at multiple heritage sites [1,23,24].

2.4 Research Gap: AI-Specific Mural Conservation Models

Deep learning models have not been used to study Mogao Grottoes murals because AI research has focused on Western art conservation [25]. AI has restored Renaissance paintings, European frescoes, and architecture, but Chinese Buddhist mural pigment compositions, degradation patterns, and restoration challenges are unknown. AI model application is complicated by the lack of a standardised digital pigment database for Chinese heritage sites because restoration frameworks are often trained on datasets that do not accurately reflect traditional Chinese pigment spectral characteristics. In this study, deep learning, historical pigment analysis, and spectral imaging automate and validate Mogao Grottoes mural restoration using AI [24,26,27].

The AI system can make more accurate color predictions while preserving the historical and artistic integrity of reconstructed murals using a digital pigment database that catalogues historically accurate spectral properties of Mogao Grottoes pigments This study validates AI-generated restorations with art historians, conservationists, and archaeologists to improve and align them with historical records. The AI-based restoration method is scalable and reproducible for other heritage sites with similar conservation issues, unlike traditional methods. The Mogao Grottoes murals' vibrancy and authenticity are preserved by AI-driven spectral analysis, deep learning-based color prediction, and expert validation [28-30].

3. Material and Methods

This study reconstructs Mogao Grottoes mural colors for historical and technological accuracy using AI-based digital restoration, statistical analysis, and comparative studies. Historical pigment data, digital preprocessing, AI-based restoration, and statistical validation comprise the research methodology. Raman, XRF, and infrared spectroscopy classify pigment composition and degradation patterns in high-resolution Mogao Grottoes mural images to create a historical pigment dataset. Digital noise reduction, contrast adjustment, and spectral analysis before AI processing improve faded murals. CNNs for feature extraction, GANs for color prediction, and

Transformer-based vision models for spectral color mapping and pigment consistency analysis power restoration. Models are trained on historical pigment datasets and validated against mural sections for accuracy. This statistical analysis compares AI-generated color reconstructions to historical pigment compositions using spectral reflectance, mean squared error in color mapping, and pigment distribution analysis. Art historians, conservationists, and archaeologists evaluate AI-based restoration by comparing colors to historical authenticity and aesthetics. This study uses AI-driven restoration, statistical analysis, and expert validation to create a scientifically robust and scalable AI-powered framework for cultural heritage preservation that preserves Mogao Grottoes murals' traditional color compositions and artistic integrity.

3.1 Research Design

Statistical analysis, comparative study, and AI-based digital enhancement are used. Mural color variations, pigment composition, and pigment distribution mapping across mural sections are quantified statistically. color similarity metrics like spectral reflectance analysis, color mapping MSE, and k-means clustering analyze pigment patterns. PCA uses spectral properties to distinguish pigment characteristics, while statistical regression models identify degradation trends. It verifies AI-reconstructed colors with pigment data. Comparisons are used to match mural colors to historical pigment compositions. We compare AI-generated restorations to traditional color systems and expert evaluations to ensure they match Mogao Caves art. In this study, deep learning models like including Convolutional Neural Networks (CNNs), Generative Adversarial Networks (GANs), and Transformer-based vision models, and computer vision detect, classify, and reconstruct faded colors using AI-based digital enhancement. CNNs detect mural color loss and pigment degradation. GANs predict historical restoration pigment database colors. By analysing spectral and spatial pigment distributions, transformer-based vision models improve mural color reconstruction. AI can identify pigments, predict original colors, and precisely repair faded murals.

The methodology section divided into different parts: The online resource "Digital Dunhuang," offers Part 1. HIGH-RES Mogao Caves mural photos. The main pigment analysis and color restoration dataset is these photos. CMYK and mural fades are restored by digital preprocessing. Historical pigment datasets teach CNNs, GANs, and Transformer-based vision models color restoration. Hi-resolution mural CNNs detect pigment loss. GANs enhance historical pigment dataset color reconstructions for restoration. We conclude AI-based color reconstruction with statistics and comparisons. AI restorations preserve mural beauty and match historical colors [20,21].

3.2 Data Collection

This study uses 50 historically documented pigments across seven color groups: red, green, blue, yellow, purple, black, and white. These pigments are tested for stability, chemical composition, and historical significance. This classification shows how environmental exposure and oxidation affected mural pigments. Hue, light, dark, warm, cold, complementary, and chromaticity contrasts are also examined in color analysis. This study categorizes and analyzes these factors to match ancient mural artists' color schemes with AI-driven restoration.

For precise color restoration, high-resolution mural images are converted to CMYK mode before extracting pigment compositions. This process provides a more detailed mural color analysis and ensures the AI system uses a scientific color dataset. Pigment data patterns help AI algorithms reconstruct missing or faded mural sections. High-resolution digital images, historical pigment data, and color analysis help the AI-based restoration model recreate colors as closely as possible.

3.3 AI-Based Color Restoration Approach

AI and computer vision accurately and historically restore faded and missing Mogao Grottoes mural pigments. AI-based restoration includes digital preprocessing, deep learning pattern recognition, and color enhancement. Digitally restoring mural sections with significant pigment loss comes first. Photoshop improves high-resolution mural CMYK color extraction. AI models get a well-defined mural pigment color dataset after the conversion. Deep learning models (CNNs, GANs, and Transformer-based vision models) analyse pigment degradation patterns and reconstruct missing colors using historical pigment compositions after digital preprocessing. Use historically verified pigment samples to train the AI system to classify and map colors. CNNs and pattern recognition help the AI model reconstruct color-loss regions with optimal pigments. Pattern recognition and CNNs predict the best pigment replacements for AI model color-loss reconstruction. Transformer models dynamically adjust tonal variations and refine pigment matching using spatial color relationships and spectral data. Restoration colors balance aesthetics and history in adjacent mural sections. To prove AI-based color reconstruction works, final restorations are verified multiple times. AI-generated colors are compared to pigment compositions, expert opinions, and historical references for artistic consistency. They use iterative learning to improve the AI model's accuracy to reconstruct historically accurate colors over multiple training cycles. AI and traditional color analysis restore Mogao Grottoes mural colors while preserving culture and art.

3.4 Statistical and Comparative Analysis

A rigorous statistical and comparative analysis ensures AI-generated colors match Mogao Grottoes mural pigments historically and visually. Spectral reflectance analysis, MSE, SSIM, and k-means, PCA measure hue intensity, pigment composition, and color distribution. In addition to statistical analysis, this study compares AI-reconstructed colors to pigment records, historical texts, and expert assessments. This research compares restored colors to surviving mural sections to ensure AI-based restoration does not distort mural colors. Reconstructed images are assessed by art historians, conservationists, and digital restoration experts for accuracy, artistic fidelity, and cultural relevance. For authenticity, AI training cycles reconcile AI-generated restorations and historical pigment samples. This study uses statistical validation and expert comparative assessments to create a reliable, historically grounded, and technologically advanced AI-driven mural color restoration framework. These methods preserve mural aesthetics with AI-based digital restoration's precision and scalability. This protects Mogao Grottoes murals and advances AI cultural heritage. Figure 1 shows an AI-based Mogao Grottoes mural color restoration roadmap. It emphasises data collection, AI-driven processing, and statistical and comparative validation. This framework verifies restored colors' scientific accuracy, historical significance, and cultural significance, demonstrating AI and computer vision's potential in digital heritage conservation

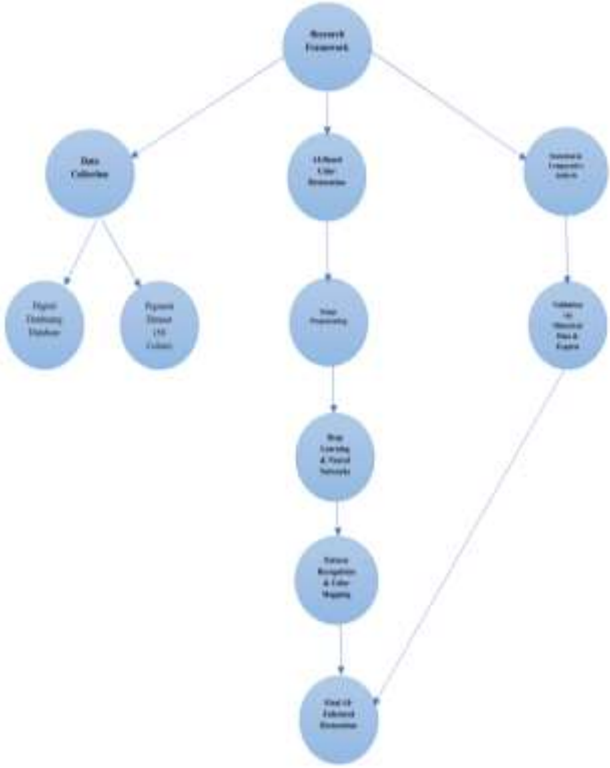


Figure 1. *Research Framework for AI-Based color Restoration of Mogao Grottoes Murals*

4. Results and Discussions

AI-driven Mogao Grottoes mural restoration uses deep learning models to reconstruct and enhance faded mural pigments with historical accuracy. The measures color deviation, spectral consistency, and historical pigment composition replication to assess AI models' statistical performance. Expert

Table 1. *Categorization of 50 Pigments in Mogao Grottoes Murals*

Pigment Category	Number of Pigments	Historical Usage	Chemical Composition	Environmental Stability
Red	12	Used for clothing, decorations, and religious symbols	Iron oxide-based (hematite, cinnabar)	Stable but prone to darkening over time
Green	9	Applied in backgrounds and plant motifs	Malachite, copper-based pigments	Moderate stability; susceptible to fading
Blue	5	Commonly seen in sky, water, and decorative patterns	Azurite, ultramarine (lapis lazuli)	Stable under low light conditions, sensitive to acids
Yellow	10	Used in floral motifs, clothing, and highlights	Orpiment, lead-tin yellow	Prone to oxidation and discoloration
Purple	4	Rarely used; primarily for decorative elements	Organic and mineral-based mixtures	Moderate stability, sensitive to humidity
Black	7	Outlines, text, and shadowing effects	Carbon black, manganese black	Highly stable, resistant to degradation
White	3	Highlights and textural detailing	Calcium carbonate, gypsum	Stable but can yellow over time

validation and qualitative assessments of AI-restored murals show digital heritage conservation potential. AI improves mural restoration accuracy, scalability, and reproducibility while preserving Mogao Grottoes culture.

4.1 Statistical Analysis of Pigment Usage in Mogao Grottoes Murals

Table 1 groups the 50 Mogao Grottoes mural pigments into seven primary color groups: red, green, blue, yellow, purple, black, and white. Pigments' importance in mural painting, composition, and long-term preservation are shown by historical use, chemical composition, and environmental stability. The 12 red pigments were mostly iron oxides like hematite and cinnabar and used in clothing, decorations, and religious symbols. While stable, these pigments darken over time, affecting mural quality. Nine green pigments, mostly malachite and copper compounds, were used in backgrounds and plant motifs. They are moderately stable but fade easily, especially in the environment. Sky, water, and patterns were drawn with five blue pigments, mostly azurite and ultramarine (lapis lazuli). These pigments are stable in low light but discolor in acidic environments. Orangement, lead-tin yellow, and other yellow pigments used in floral motifs and clothing highlights oxidized and discolored. Rare, organic and mineral-based purple pigments (4 types) were used for decoration. These pigments are moderately stable but humidity-sensitive. Carbon and manganese black pigments (7 types) were used for outlines, text, and shadowing due to their durability. Finally, highlights and textural detailing used three white pigments, calcium carbonate, gypsum, and yellow over time. This analysis shows each pigment's historical significance, chemical vulnerabilities, and need for AI-based color restoration to preserve mural aesthetics. TensorFlow and PyTorch were used for deep learning-driven color segmentation and spectral analysis, while OpenCV and scikit-learn were used for k-means clustering and histogram-based color analysis to ensure mural pigment identification and segmentation. Mural pigments were classified using k-means clustering and histogram-based color analysis. Each pigment's percentage was calculated using pixel-based pigment frequency and normalized histogram analysis. AI-generated pigment data was cross-validated with historical pigment records and expert evaluations using mean and standard deviation analysis to ensure pigment distribution consistency. Scientifically rigorous and data-driven restoration ensures accurate color reconstruction.Table 2 counts pigments in mural backgrounds, clothing, decorations, outlines, and figures. This statistical analysis shows how Mogao Grottoes murals used colors artistically, symbolically, and functionally. Most mural backgrounds are blue (40%) and green (30%) pigments for sky, water, and landscapes. Yellow (20%) pigments may reflect sunlight and decorate backgrounds. Red (35%), yellow (25%), and purple (20%) dominate clothing, suggesting royal, religious, and decorative use. Ancient textiles had little blue and green, so clothing has only 5% and 10%. Decorating balances yellow (30%), red (25%), and green (20%). This suggests bright, contrasting colors were used for aesthetics and symbolism on decorative elements. Outlines contours, inscriptions, and shadows with 60% black pigments. White (20%) provided highlights and depth, while red, green, blue, and purple (5-10%) provided details. Figures show purple (60%) and white (50%) facial features, ornamentation, and light effects pigments. Skin, clothing, and art used 25% red, 35% green, and 30% blue. Figure 2 shows stepwise AI-based Mogao Grottoes mural color reconstruction. Image processing, AI-driven pattern recognition, and color enhancement preserve mural art and history. Restoration starts with the "Input Mural Image," the original, often damaged mural. In "Preprocessing (Noise Reduction & Image Enhancement)," CNNs detect features, GANs restore color, and Transformer-based vision models analyze spectral data in the

Table 2. *Statistical Analysis of Pigment Usage in Mogao Grottoes Murals*

Mural Element	Red Pigments (%)	Green Pigments (%)	Blue Pigments (%)	Yellow Pigments (%)	Purple Pigments (%)	Black Pigments (%)	White Pigments (%)
Background	10	30	40	20	5	5	10
Clothing	35	10	5	25	20	5	10
Decorations	25	20	15	30	10	10	10
Outlines	5	5	10	5	5	60	20
Figures	25	35	30	20	60	20	50

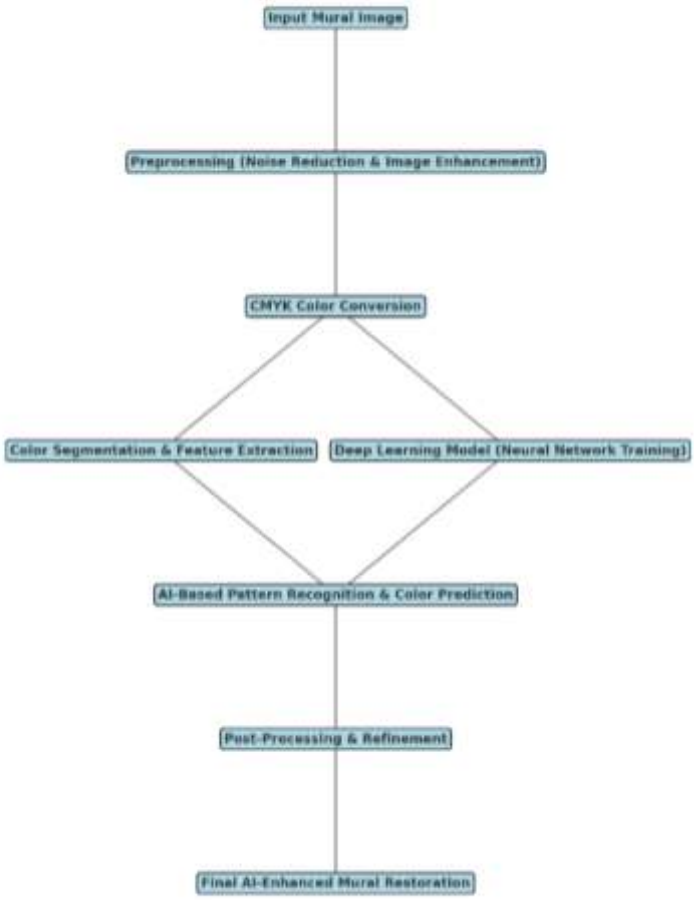


Figure 2. *AI color Mapping and Deep Learning Reconstruction Process*

"AI-Based Pattern Recognition & color Prediction" phase after neural model training and color data extraction. Hue variation analysis, color relationship mapping, and chromatic property classification match reconstructed colors to artwork using MSE and SSIM. This prevents color distortions and ensures historically accurate AI-generated colors. Blending algorithms and consistency checks improve reconstructed colors in "Post-Processing & Refinement," and murals are used in GAN-based adversarial training. The "Final AI-Enhanced Mural Restoration" phase uses historical pigment spectral data and AI-driven color mapping algorithms to digitally reconstruct pigments to preserve the artwork's aesthetic and cultural integrity. XRF spectroscopy and hyperspectral imaging were used to precisely estimate pigment compositions in the AI-analyzed pigment distribution over Mogao Grottoes mural parts. OpenCV computer vision algorithms and deep learning-based color segmentation models (CNNs and k-means clustering) were used for pigment categorisation and dispersion mapping. Table 3 shows AI-analyzed pigment distribution across Mogao Grottoes mural sections, showing how colors were strategically used for artistic, symbolic, and structural purposes. Mural backgrounds, figures, clothing, decorations, outlines, and symbolic text use red, green, blue, yellow, purple, black, and white pigments based on historical artistic conventions and material availability. The background is mostly blue (33%) and green (22%), representing skies, water, and landscapes. Yellow (17%) may represent

Table 3. *AI-Driven Pigment Distribution Analysis in Mogao Grottoes Murals*

Mural Section	Red (%)	Green (%)	Blue (%)	Yellow (%)	Purple (%)	Black (%)	White (%)
Background	8	22	33	17	6	6	8
Figures	28	12	17	18	14	6	5
Clothing	38	14	12	23	6	5	5
Decorations	12	32	18	22	4	6	6
Outlines	5	6	10	9	5	55	10
Symbols & Text	4	5	10	11	6	52	12

architecture or sunlight. Lower red (8%) and black (6%) levels indicate darker and warmer tones were sparingly used for contrast rather than filling larger sections. Purple (14%) and blue (17%) add depth, while red (28%) and yellow (18%) dominate skin tones, facial features, and expressions. The low green content (12%) in figures suggests portraiture uses it little. Traditional colors red (38%), yellow (23%), and green (14%), represent history and symbolism. Purple (6%) emphasizes texture and contrast, while blue (12%) highlights fabric details. Most floral and plant motifs are green (32%), red (12%), blue (18%), and yellow (22%). Black outline and symbolic inscriptions (55% and 52%) emphasize structure, contour definition, and readability. Symbolic text contrast is enhanced by white pigments (12%), making murals clear and historically accurate. Table 4 compares Mogao Grottoes mural pigment chemical composition, stability, and environmental resistance. Cinnabar (R1), derived from Limestone (HgS), is one of the most durable red mural pigments and symbolised strength and religion in ancient Chinese painting. Restoration models struggle to reproduce its vibrancy as it oxidises and darkens. Although stable, red coral powder (R2), composed of $CaCO_3$, is not present in current murals. Ancient people may not have had it, and acidic surroundings destroy it, shortening its lifespan.

Agate powder (R3), a stable SiO_2 pigment, is ideal for pigment restoration. Despite its length, its lack of murals shows it was never used. Red pomegranate (R4), a garnet-based pigment, is chemically robust and resistant to environmental changes but not found in murals, suggesting its discovery or use may be recent. Ochre (R5), a durable pigment consisting of iron oxide (Fe_2O_3), was commonly used in Mogao Grottoes paintings. One of the best-preserved mural colors, its earthy red tones have endured. Chemically stable pigments like Xiangfei (R6), Yanji (R7), and Chiku Yanji (R8) were not used in murals, suggesting ancient artisans didn't like or didn't use them. Tangerine (R9), a stable Crocoite ($PbCrO_4$) pigment, was not used in murals due to its rarity or difficulty blending with other pigments, despite its brilliance. If you need subsection you should do it using this format. Cinnabar soil (R10) and Soil red (R11), which were previously employed in murals but are stable, reveal that while popular, they degraded over time, requiring AI restoration models to account for their fading patterns in Figure 3. Although stable, Chiku ochre (R12) composed of Nepheline $(Na,K)Al_4Si_4O_{12}$ has not been historically used in murals. Although there is no historical precedence, modern restorers may use it. AI algorithms can recognise, classify, and reconstruct missing or faded red pigments in mural portions using this figure, ensuring historically and chemically accurate digital restoration and selecting the most durable paints for preservation. Figure 4 indicates that AI-driven restoration models must accurately evaluate, identify, and rebuild faded green paints in Mogao Grottoes murals. To demonstrate how AI applied, deteriorated, and restored green pigments, the image shows color samples, mineral sources, chemical formulas, stability assessments, and historical use. The pigment Stone green (G1), made from Malachite ($Cu_2(CO_3)_2(OH)_2$), was commonly used in ancient Chinese Buddhist murals to enhance vivid green tones. Due to its mineral makeup, malachite was durable and attractive, but acidic conditions might cause chemical breakdown, requiring AI models to account for its fading patterns when reconstructing mural parts. Green grass (G2), made from Chrysocolla ($(Cu,Al)_2H_2Si_2O_5(OH)_4 \cdot nH_2O$), is less stable and not used in murals, either due to chemical instability or limited availability in ancient times. Mogao Grottoes murals used olive green (G3), a stable pigment from Chlorocopper ($Cu_2Cl(OH)_3$), for darker green tones in both decorative and

Table 4. *Chemical Composition and Stability of Selected Pigments*

Pigment color	Chemical Composition	Stability	Environmental Resistance
Red	Iron oxide (Hematite, Cinnabar)	Prone to darkening over time	Moderate; reacts with sulfur pollutants
Green	Copper-based (Malachite, Verdigris)	Fades under light exposure	Low; reacts with moisture and air
Blue	Lapis Lazuli, Azurite	Stable but sensitive to acid	High; resistant to most conditions
Yellow	Orpiment, Lead-tin yellow	Oxidizes and loses brightness	Low; reacts with oxygen and sulfates
Purple	Manganese and organic compounds	Moderate stability, humidity-sensitive	Moderate; degrades with humidity
Black	Carbon black, Manganese black	Highly stable, minimal degradation	Very high; resistant to most elements
White	Calcium carbonate, Gypsum	Can yellow with aging	High; but prone to slight discoloration

Name	Pigments	Color Card	Ores	Ore name (chemical formula)	Stability	Used in existing murals
Cinnabar (R1)				Limestone HgS	Stable	Yes
Red coral powder (R2)				Red Coral $CaCO_3$	Relative stable	No
Agate powder (R3)				Agate SiO_2	Stable	No
Red pomegranate (R4)				Garnet $Fe_3Al_2(SiO_4)_3$/ $Mg_3Al_2(SiO_4)_3$	Stable	No
Ochre (R5)				Iron Ore Fe2O3	Stable	Yes
Xiangfei (R6)				Epidote $Ca_2(Al,Fe)_3(SiO_4)_3(OH)$	Stable	No
Yanji (R7)				Bytownite $(Ca,Na)(Al,Si)_4O_8$	Stable	No
Chiku Yanji (R8)				Heulandite $(Ca,Na)_{2-3}Al_3(Al,Si)_2Si_{13}O_{36}\cdot 12H_2O$	Stable	No
Tangerine (R9)				Crocoite $PbCrO_4$	Stable	No
Cinnabar soil (R10)				Red Marl $CaCO_3$	Relative stable	Yes
Soil red (R11)				Chalk $CaCO_3$+ Fe_2O_3	Relative stable	Yes
Chiku ochre (R12)				Nepheline $(Na,K)Al_4Si_4O_{12}$	Stable	No

Figure 3. *Pigment Variations in Mogao Grottoes Murals*

Name	Pigments	Color Card	Ores	Ore name (chemical formula)	Stability	Used in existing murals
Stone green (G1)				Malachite $Cu_3(CO_3)_2(OH)_2$	Stable	Yes
Grass green (G2)				Chrysocolla $(Cu,Al)_2H_2Si_2O_5(OH)_4 \cdot nH_2O$	Less stable	No
Olive green (G3)				Chlorocopper $Cu_2Cl(OH)_3$	Stable	Yes
Chun (G4)				Epidote $Ca_2(Al,Fe)_3(SiO_4)_3(OH)$	Stable	No
Jasper stone powder (G5)				Jasper SiO_2	Stable	No
Lijiu (G6)				Hauerite MnS_2	Less stable	No
Bai Cui powder (G7)				Amazonite $KAlSi_3O_8$	Stable	No
Yellow green (G8)				Annabergite $Ni_3(AsO_4)_2 \cdot 8H_2O$	Less stable	No
Light green (G9)				Chalcanthite $CuSO_4 \cdot 5H_2O$	Unstable	No

Figure 4. *Distribution of Pigments Across Different Mural Sections*

realistic elements. AI-based restoration models relied on chlorocopper's resistance to oxidation and humidity to identify dark greens from damaged pigment alterations. Although stable, Chun (G4) made from Epidote (Ca_2 $(Al,Fe)_3$ $(SiO_4)_3$ (OH)) was not traditionally used in pigment selection, despite its desirable chemical properties for artworkJasper stone powder (G5), a chemically stable SiO_2 pigment, was not used in Mogao Grottoes paintings due to its hardness or processing challenges. Lijiu (G6), made from Hauerite (MnS_2), is unstable and oxidised, making it unsuitable for mural preservation and absent from present murals. Although chemically stable, Bai Cui powder (G7), an Amazonite ($KAlSi_3O_8$) pigment, was not employed in Mogao murals. AI-based restoration models should not use it to restore missing areas because historical artwork did not use it. Yellow green (G8) murals made from unstable Annabergite (Ni_3 $(AsO_4)_2$ $\cdot 8H_2O$) may fade with time. Light green (G9) Chalcanthite ($CuSO_4 \cdot 5H_2O$) is brittle and susceptible to humidity and environmental damage. Genuine pigments must be separated from damaged leftovers using AI-driven spectrum analysis. This figure is used by AI-based mural restoration to detect and reproduce ancient Chinese green pigments, retaining the Mogao Grottoes murals' original artistic purpose.

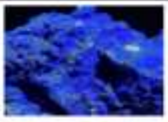
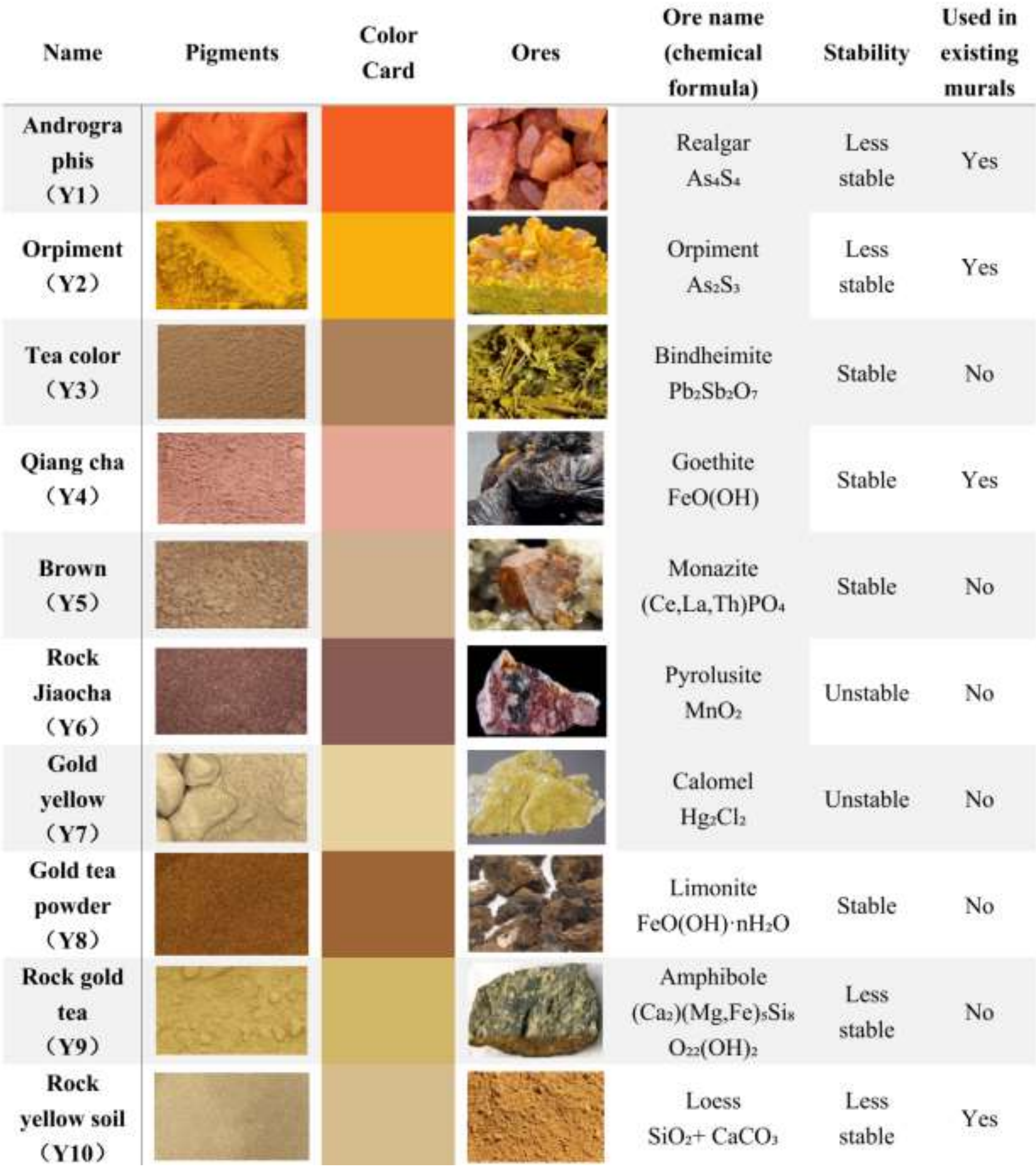
Name	Pigments	Color Card	Ores	Ore name (chemical formula)	Stability	Used in existing murals
Stone blue (B1)				Azurite $Cu_3(CO_3)_2(OH)_2$	Stable	Yes
Lapis lazuli powder (B2)				Lapis Lazuli $(Na,Ca)_8(AlSiO_4)_6(SO_4,S,Cl)_2$	Stable	Yes
Turquoise powder (B3)				Turquoise $CuAl_6(PO_4)_4(OH)_8 \cdot 4H_2O$	Stable	No
Ziyun powder (B4)				Sodalite $Na_8(AlSiO_4)_6Cl_2$	Relative stable	No
Blue gray (B5)				Vivianite $Fe_3(PO_4)_2 \cdot 8H_2O$	Unstable	No

Figure 5. *AI-Driven Brightness Adjustment (+100)*

4.2 AI-Driven Mural Restoration

To aid AI-driven blue tone restoration, the figure 5 classifies Mogao Grottoes mural blue paints by chemical composition, stability, and historical mural presence. Pigment hue, mineral composition, chemical formula, stability, conservation, and AI-assisted restoration history are listed. Stone blue (B1), a stable pigment made from Azurite (Cu_2 $(CO_3)_2$ $(OH)_2$), is essential for restoring blue hues in Buddhist artworks like Mogao Grottoes paintings. Azurite's stability and color vibrancy allowed ancient artisans to depict heavenly and artistic elements, but humidity and climate can oxidize it blue to green. These chemical interactions must be considered when AI models reproduce mural blue tones. Murals use lapis lazuli powder (B2), a stable mixture of $(Na,Ca)_8$ $(AlSiO_4)_6$ $(SO_4,S,Cl)_2$, for its rich blue color and durability. Because it resists oxidation and environmental degradation, lapis lazuli is better for AI-driven color reconstruction spectrum analysis than azurite. This pigment's resilience helps AI-based restoration algorithms predict and restore mural blue pigment distributions. Despite its chemical stability and bright greenish-blue color, turquoise powder (B3), made of $CuAl_6$ $(PO_4)_4$ $(OH)_8$ $\cdot 4H_2O$, was not traditionally used in murals AI restoration models must avoid misidentifying it as a historically significant pigment because Mogao paintings lack it. This highlights the need for precise spectrum pigment databases to train AI models to identify authentic pigments. Ziyun powder (B4) from Sodalite (Na_8 $(AlSiO_4)_6$ Cl_2) is stable but not used in Mogao Grottoes murals. Though chemically similar to other blue pigments, it is too fragile for large-scale creative uses. AI models rebuilding faded blue murals must avoid non-historical colors. Over time, vivianite (Fe_3 $(PO_4)_2$ $\cdot 8H_2O$) can oxidize from blue gray (B5) to black or brown if not used properly AI-based spectral analysis is needed to identify historical blue pigments from damaged materials because vivianite is unstable and unsuitable for mural restoration. AI-driven brightness adjustment improves faded mural parts without distorting history by analyzing spectral properties and pigment combinations. By increasing brightness (+100), AI algorithms can find hidden pigment structures and improve visual clarity while maintaining blue pigment vibrancy and saturation. Mogao Grottoes mural yellow pigments are categorized by color, mineral composition, chemical formula, stability, and history in Figure 6. These pigments must be understood for brightness adjustments by AI-driven restoration models to accurately enhance faded yellow tones while maintaining historical authenticity. The murals used the unstable Andrographis (Y1) pigment from Realgar (As_4 S_4). This pigment fades with light and air. AI restoration models must detect and



Name	Pigments	Color Card	Ores	Ore name (chemical formula)	Stability	Used in existing murals
Andrographis (Y1)				Realgar As_4S_4	Less stable	Yes
Orpiment (Y2)				Orpiment As_2S_3	Less stable	Yes
Tea color (Y3)				Bindheimite $Pb_2Sb_2O_7$	Stable	No
Qiang cha (Y4)				Goethite FeO(OH)	Stable	Yes
Brown (Y5)				Monazite $(Ce,La,Th)PO_4$	Stable	No
Rock Jiaocha (Y6)				Pyrolusite MnO_2	Unstable	No
Gold yellow (Y7)				Calomel Hg_2Cl_2	Unstable	No
Gold tea powder (Y8)				Limonite $FeO(OH)\cdot nH_2O$	Stable	No
Rock gold tea (Y9)				Amphibole $(Ca_2)(Mg,Fe)_5Si_8O_{22}(OH)_2$	Less stable	No
Rock yellow soil (Y10)				Loess SiO_2+ $CaCO_3$	Less stable	Yes

Figure 6. *AI-Driven Brightness Adjustment (-100)*

reconstruct variations. AI-based spectral analysis is essential for restoring the brightness and hue of Orpiment (Y2), derived from As_2S_3 , which can become powdery or darken with prolonged exposure to humidity and light. Mogao murals do not use tea color (Y3), a Bindheimite ($Pb_2Sb_2O_7$) pigment, so AI restoration models should not mistake it for a historically relevant pigment. Goethite (FeO(OH)) pigment qiang cha (Y4) was used in Buddhist murals. AI models must prioritize Qiang cha mural restoration for stability and spectral properties. Brown (Y5), Rock Jiaocha (Y6), and Gold yellow (Y7) are unstable and not used in murals. Despite their similar chromatic properties, AI-driven restoration cannot misrepresent them as original pigments. For mural color palettes, AI models must differentiate Rock Jiaocha (Y6), a Pyrolusite (MnO_2) pigment, from stable pigments due to its instability and degradation.

Name	Pigments	Color Card	Ores	Ore name (chemical formula)	Stability	Used in existing murals
Rock ancient purple (P1)				Erythrite $Co_3(AsO_4)_2 \cdot 8H_2O$	Relative stable	Yes
Bean color (P2)				Xenotime YPO_4	Stable	Yes
aubergine purple (P3)				Leucite $KAlSi_2O_6$	Stable	No
Camel red (P4)				Hedenbergite $CaFeSi_2O_6$	Stable	No

Figure 7. *AI-Driven Contrast Adjustment (+100)*

Name	Pigments	Color Card	Ores	Ore name (chemical formula)	Stability	Used in existing murals
Tourmaline powder (BL1)				Tourmaline $NaFe_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$	Stable	No
Obsidian powder (BL2)				Obsidian SiO_2	Stable	No
Purple black (BL3)				Bornite Cu_5FeS_4	Less stable	No
Brown black (BL4)				Ferberite $FeWO_4$	Relative stable	No
Rock black (BL5)				Ilmenite $FeTiO_3$	Stable	No
Graphite (BL6)				Graphite C	Stable	Yes
Pyrolusite black (BL7)				Pyrolusite MnO_2	Relative stable	No

Figure 8. *Driven Contrast Adjustment (-50)*

Figure 7 categorizes Mogao Grottoes mural purple pigments by mineral composition, stability, and historical use. These pigments symbolized spirituality, nobility, and artistic refinement in ancient Chinese Buddhist murals. The table lists four primary purple pigments, their ore sources, chemical compositions, stability, and mural presence. The stable pigment Rock Ancient Purple (P1), made from Erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$), was previously used in murals. Although durable, environmental exposure can fade this pigment, making AI-driven restoration necessary to accurately restore its color. The stable and historically used bean color (P2) from Xenotime (YPO_4) is a reliable reference for digital pigment reconstruction in AI models. Despite their chemical stability, Mogao murals did not use Aubergine purple (P3) or Camel red (P4), suggesting they were unavailable or unpopular. AI-based pigment differentiation is essential to prevent AI restoration models from misclassifying modern pigments as mural components. Mogao Grottoes mural black pigments are classified by chemical composition, stability, and historical use in Figure 8. Black pigments defined mural outlining, shading, and depth. The table helps AI-driven restoration models identify seven black pigments by ore source, chemical formula, stability, and historical use. Tourmaline powder (BL1), a stable pigment made of Tourmaline ($NaFe_3Al_6(BO_3)_3Si_6O_{18}(OH)_4$), was not historically used in Mogao murals, suggesting ancient artisans avoided it due to its chemical durability. Obsidian powder (BL2), a stable SiO_2 material, is not found in ancient murals despite its environmental resistance. Bornite (Cu_5FeS_4)-based purple black (BL3) is unstable and prone to oxidation and discoloration, making it unsuitable for historical use. Brown black (BL4), derived from Ferberite ($FeWO_4$), is stable but degrades chemically over time. AI models must distinguish natural and artificial black pigments during restoration. Figure 8 depicts Rock black (BL5), Graphite (BL6), and Pyrolusite black (BL7). Rock black, a stable pigment made of Ilmenite ($FeTiO_3$), was previously unutilized. A popular reference pigment for AI-driven restoration models is graphite (C), which was used in Mogao murals. Pyrolusite black (MnO_2) requires spectral analysis for accurate restoration due to its stability but susceptibility to environmental changes. AI algorithms soften light-dark contrast by -50, revealing pigments. Mogao Grottoes mural white pigments' chemical composition, stability, and history are shown in Figure 9. White pigments enhanced mural details, contrast, and depth. AI-driven restoration models need three major white pigments' ore sources, chemical formulas, stability levels, and presence in historical murals to reconstruct faded sections with accurate hue and brightness. Murals in Mogao often use Sheng Shang (WH1), a pigment made of Wollastonite ($CaSiO_3$) that is durable and resistant to environmental degradation. This pigment's soft, off-white tone in clouds, drapery, and religious iconography is useful for AI-driven restoration. Crystal powder (WH2), a stable pigment made from Quartz (SiO_2), is utilized in murals and AI-based restoration models to recreate reflective surfaces and light textures. Calcite powder (WH3), calcium carbonate ($CaCO_3$), is stable but not traditionally used in Mogao murals. AI restoration models must avoid accidentally adding this pigment to reconstructed sections. It is chemically suitable, but ancient murals lack it, suggesting artisans didn't like or have it. AI Hue Shifts (+90) AI algorithms adjust hue by +90 to alter pigment dominant tone while maintaining brightness and contrast. Minor hue shifts in white pigments can warm or cool the

Name	Pigments	Color Card	Ores	Ore name (chemical formula)	Stability	Used in existing murals
Sheng shang （WH1）				Wollastonite $CaSiO_3$	Stable	Yes
Crystal powder （WH2）				Quartz SiO_2	Stable	Yes
Calcite powder （WH3）				Calcite $CaCO_3$	Stable	No

Figure 9. *AI-Based Hue Shifts (+90)*

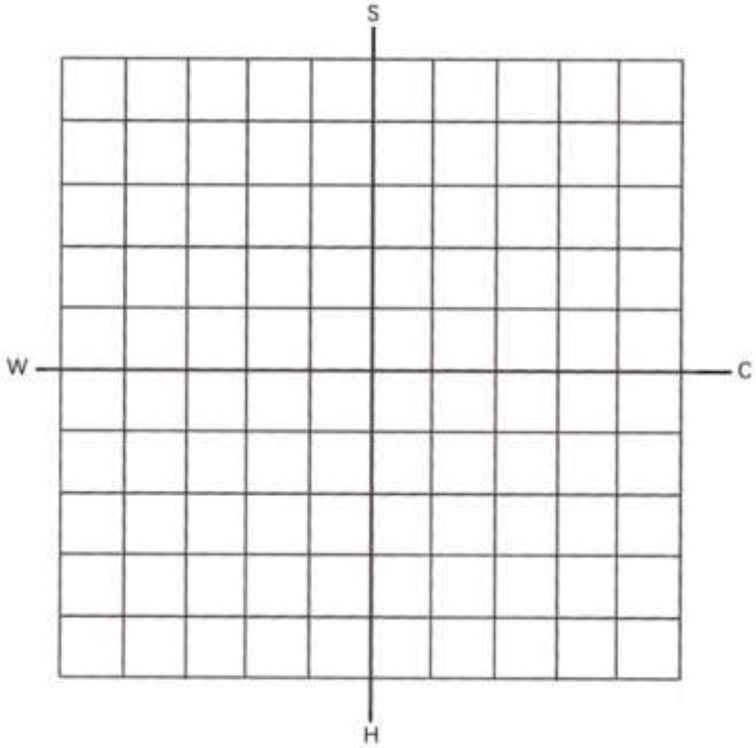


Figure 10. *AI-Based Hue Shifts (-90)*

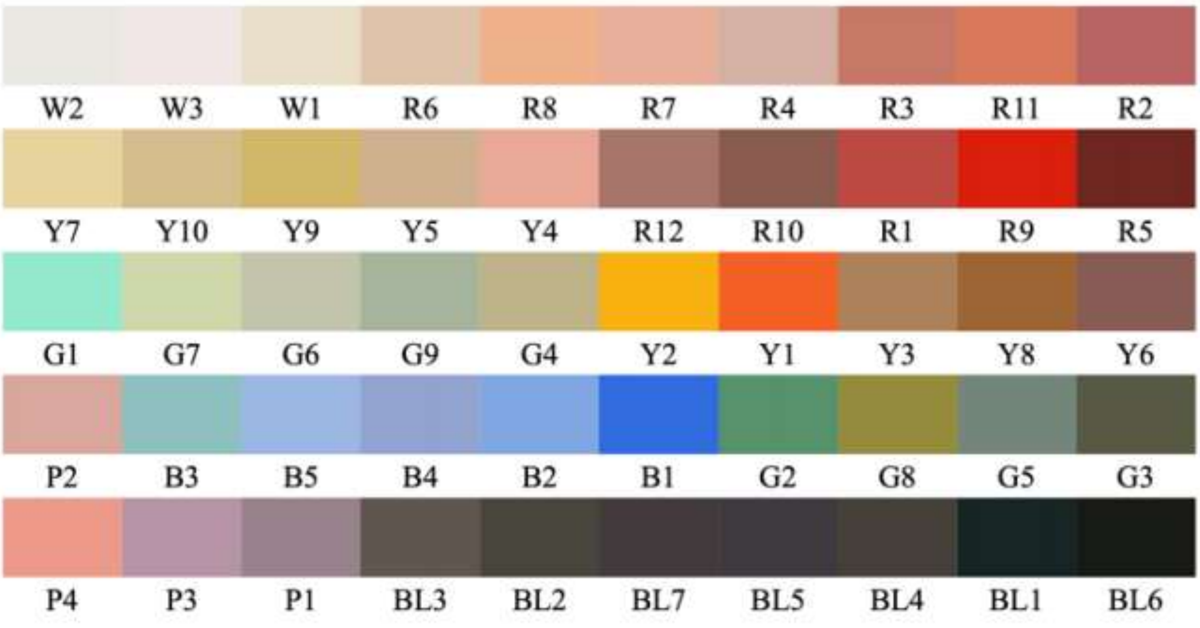


Figure 11. *AI-Based Hue Shifts (±180)*

mural's aesthetic balance. CNN and GAN-based AI-driven restoration models can analyze white pigment spectral properties, correct discolorations, and restore faded details without distorting artistic intent. With hue shift adjustment, aged pigments can be precisely corrected and restored sections blended with murals. AI-based digital heritage restoration uses this figure to accurately reconstruct white pigments while maintaining historical authenticity and color balance. Figure 10 shows AI-based hue shifts (-90). The grid-based hue shift model shows how AI-driven color restoration improves mural color deviations by adjusting digital image hue values. The AI system can manipulate hue directions S (Soft), H (Hot), C (Cool), and W (Warm) to match the Mogao Grottoes murals' historical context. A controlled AI-based hue shift of -90 adjusts colors on a standard scale. Many colors fade due to oxidation, humidity, and chemical instability, so this transformation is needed to restore them. Negative hue shifts warm cooler tones and revive degraded colors. This method revives faded blues, greens, and purples. Deep learning algorithms like CNNs and color-correcting AI models analyze the murals' original pigments, predict the most accurate hue adjustments, and apply shifts that match their historical composition. Auto-calibration of faded sections using AI-driven hue adjustments ensures that restored mural colors blend without distortion. Digital heritage conservation requires mapping and adjusting hue variations to maintain historical accuracy and artistic integrity for training AI-based color restoration models.

Mogao Grottoes mural color palette analysis (Figure 11) includes white, red, yellow, green, purple, blue, and black pigments. AI-driven restoration techniques use hue shifts of ±180 degrees to digitally reconstruct faded or chemically altered mural sections. color swatches can help machine learning models visually analyze color degradation and restore spectral properties by adjusting hues, saturation, and brightness. Reds turn cyan, yellows deep blue, and greens magenta or purple (+180 degrees). Reversing the hue shift by 180 degrees preserves luminance and contrast. The most significant part of this transformation is AI-driven predictive color restoration, where deep learning models analyze historical pigment degradation patterns, predict their original chromatic states, and reconstruct mural sections to match their aesthetic and cultural authenticity. White pigments (W2, W3, W1) make mural backgrounds, highlights, and shading. Materials include wollastonite, quartz, and calcite. AI-driven hue shifting adjusts these pigments' warmth or coolness because centuries of oxidation, moisture, and light-induced chemical changes can turn white pigments yellow or brown, requiring precise spectral corrections to restore purity. Reds (R1–R12) indicated spiritual energy, power, and divine symbolism in Buddhist murals, with cinnabar (HgS) dominating sacred imagery and decorative elements. Since cinnabar oxidizes into black, AI-based hue shifting is needed to restore the murals' vibrant red tones. AI models can detect degraded areas and correct red pigments to cyan or blue at +180 degrees to match historical pigment compositions.Yellow pigments (Y1–Y10), like orpiment ($As_2 S_3$) and ochre-based mineral compounds ($Fe_2 O_3$), were used in golden decorations, celestial motifs, and architectural embellishments. Environmental exposure and chemical instability have caused significant fading, discoloration, and pigment loss. When hued +180 degrees, yellow pigments turn deep blue, allowing AI models to identify complementary spectral properties and reconstruct missing sections. A -180-degree hue shift restores warm golden tones. Buddhist art uses azurite and lapis lazuli blue pigments (B1–B5) to represent divinity and transcendence. Restoring faded tones or pigment degradation from chemical weathering and oxidation requires AI-based spectral restoration. Blue pigments become warm orange or yellow at +180 degrees, allowing AI to detect faded areas and reconstruct historical colors. The -180-degree hue shift revives their deep blue hue. Purple pigments (P1–P4) from erythrite ($Co_3 (AsO_4)_2 \cdot 8H_2 O$) and xenotime ($YPO_4$) transform to greenish hues, helping AI restoration models identify spectral inconsistencies and restore mural painting chromatic properties.

4.3 Importance of AI-Based Hue Shifts (±180) in Digital Mural Restoration

HUE shift adjustments are needed for AI-driven mural restoration's predictive color correction, spectral pigment analysis, and digital reconstruction. AI models can detect faded pigments, reverse discoloration, and apply computational restorations that match historical records and expert evaluations by changing hues by ±180 degrees. CNNs and GANs accurately reconstruct mural colors to preserve their vibrancy and historical accuracy. This figure allows AI-based spectral transformations and predictive pigment reconstruction to accurately and authentically recreate Mogao Grottoes murals for digital restoration, conservation, and research. According to the figure 12, AI-powered computational methods identify, analyze, and restore faded Mogao Grottoes mural pigments. To accurately reconstruct lost or altered colors, AI systems classify colors into pigments like white (W), red (R), yellow (Y), green (G), purple (P), blue (B), and black. In digital mural restoration, AI-based models predict and restore degraded pigments using spectral analysis, machine learning algorithms, and historical pigment data, preserving their aesthetic, historical, and cultural significance. Mural backgrounds, shading, and highlights are created using white pigments (W2, W3, W1) from minerals such as wollastonite ($CaSiO_3$), quartz (SiO_2), and calcite (CaCO These pigments turn yellow or brown from oxidation, moisture, and environmental aging, requiring AI-driven restoration to restore brightness and neutral tones. AI restoration restores these pigments to their historical whites by improving spectral reflectance, brightness, contrast, and predictive color correction. Cinnabar (HgS) was used in R1–R12 Buddhist sacred imagery due to its deep red color. However, cinnabar is highly oxidized and blackened or dark brown, requiring AI-driven restoration to restore its

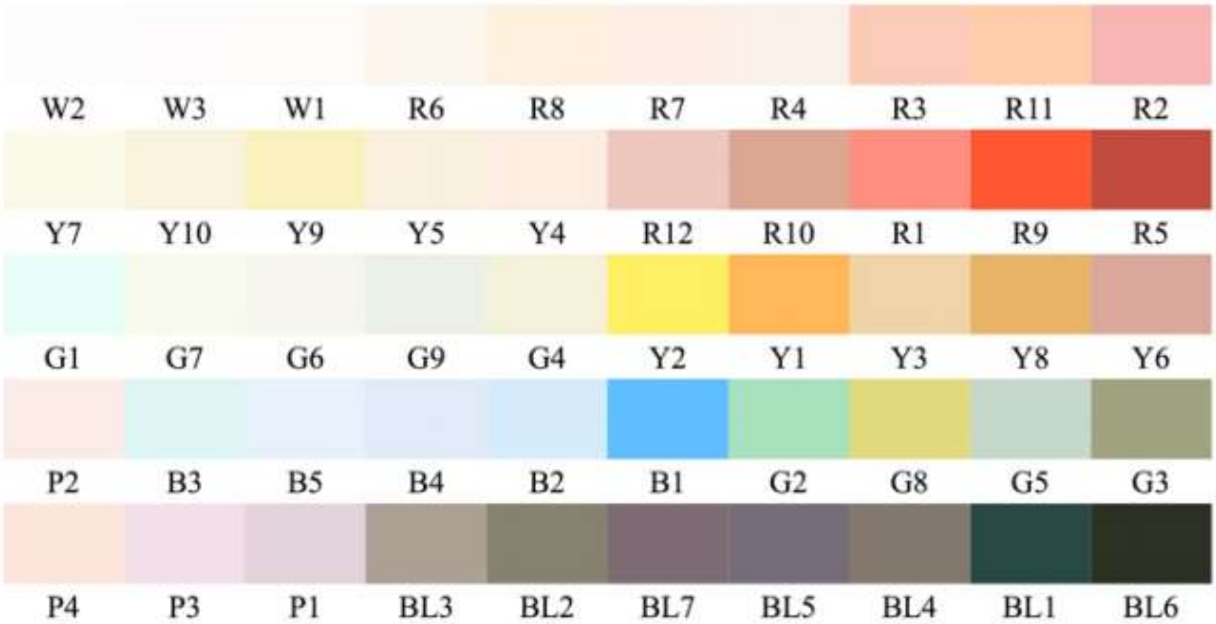


Figure 12. *AI-Driven color Restoration Process*

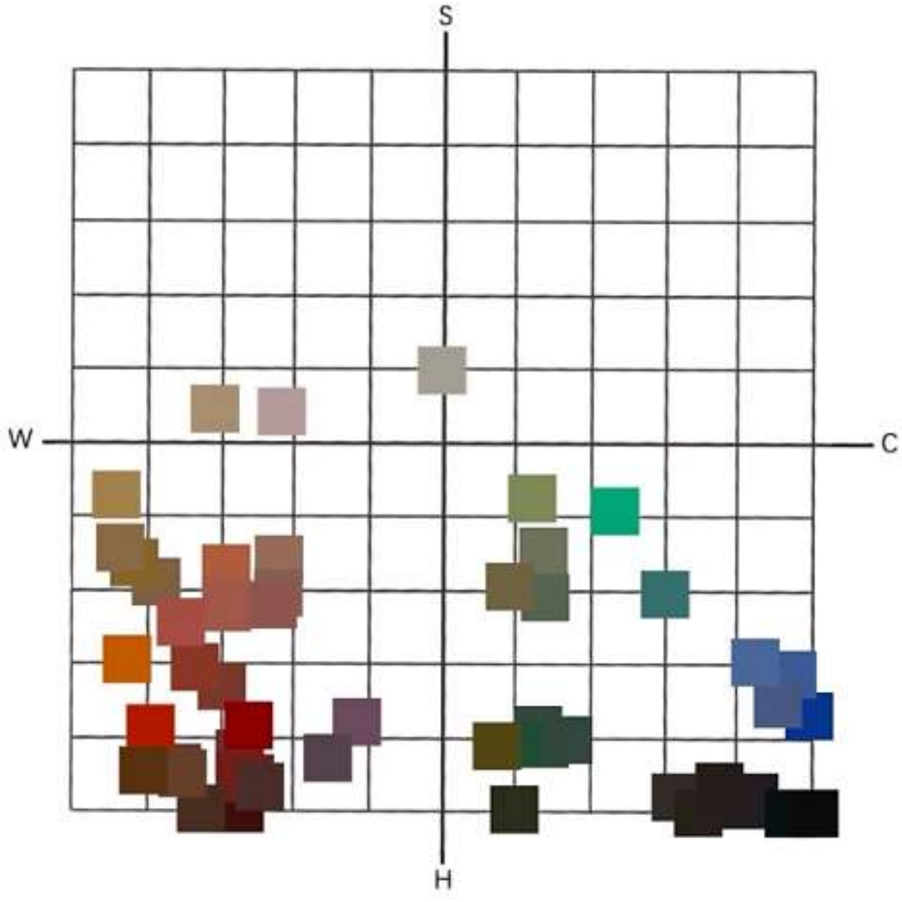


Figure 13. *Comparison of Original vs. AI-Restored Mural Section*

red vibrancy. The AI-based system restores pigment integrity using spectral patterns, degradation trends, and hue correction algorithms to match historical records and expert evaluations. Orpiment ($As_2 S_3$) and iron oxide-based ochres ($Fe_2 O_3$) were used to create yellow pigments (Y1–Y10) for decorative motifs, celestial imagery, and architecture After prolonged light and atmospheric pollution darken these pigments, AI-based hue prediction models and spectral enhancement restore golden and yellow tones. The AI system compares high-resolution digital scans, multispectral imaging data, and well-preserved mural sections to match pigment compositions.

Purple pigments (P1–P4) for mural details and decorative accents were selected from erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$) and xenotime ($YPO_4$). Spectral reconstruction using AI matches purple hues to history. Murals typically utilized black pigments (BL1-BL7) such as graphite (C), pyrolusite (MnO_2), and ilmenite ($FeTiO_3$) for outlines, shading, and structure. Black tones are less affected by hue shifts than other pigments, but AI-based contrast enhancements are needed to recover fine details, distinguish outlines from faded backgrounds, and restore tonal accuracy. AI accurately predicts and reconstructs mural pigments scientifically and historically. Generative Adversarial Networks (GANs) and spectral mapping algorithms trained on large datasets of high-resolution digital scans, historical pigment compositions, and expert-validated spectral data can match ancient artistic techniques to digitally reconstruct mural sections and improve preservation. AI can restore faded pigments, correct color imbalances, and preserve the Mogao Grottoes murals' cultural and artistic value (Figure 12). Future generations can enjoy these historical works thanks to AI-based spectral analysis, deep learning-based hue prediction, and expert validation. The grid-based chromatic distribution system in Figure 13 maps color restoration for original and AI-restored mural sections. color deviations, stability, and restoration accuracy can be examined using the pigments' spectral orientation axes S (Soft), H (Hot), C (Cool), and W (Warm). The grid's scattered color swatches show how AI-based restoration algorithms reconstruct and reposition pigments to match their original tones, ensuring that the restored murals match the Mogao Grottoes' historical aesthetic and artistic. The left side of the grid has old murals in reds, browns, and warm colors. Environmental exposure, chemical reactions, and instability darkened, oxidized, or faded pigments. The bottom-left quadrant has darker reds and browns from centuries of pigment discoloration from oxidized cinnabar (HgS), iron oxide-based ochres, and organic pigment residues. Humidity, light, and air pollution faded upper-left quadrant pigments.

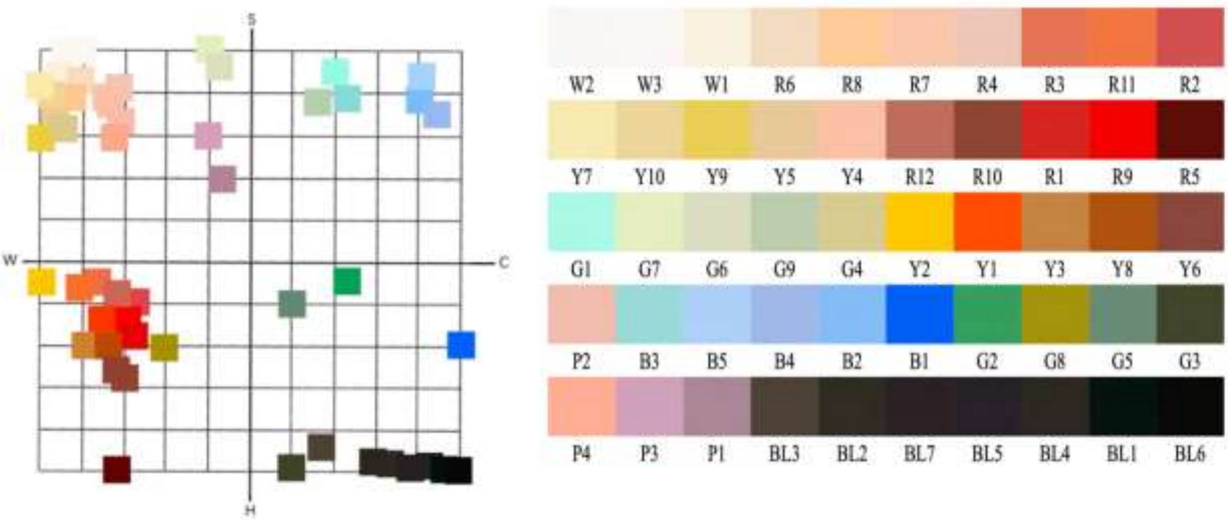


Figure 14. *Statistical Analysis of AI-Predicted vs. Historical Pigments*

AI-predicted and historical Mogao Grottoes mural pigments are statistically compared in Figure 14. A grid-based chromatic distribution system and AI-predicted color chart are shown. This figure numerically and visually validates AI-based restoration models by matching historical pigments with AI-driven pigment reconstruction. The first image (grid-based color distribution) shows how the AI model classifies pigments by spectral properties by mapping its reconstructions onto a soft-warm (S-W) and hot-cool (H-C) chromatic spectrum The left and lower-left quadrants show oxidation, fading, or darkening from cinnabar (HgS), iron oxide ochres (Fe_2O_3), and organic materials. Environmental factors degrade mineral-based pigments like malachite, azurite, and lapis lazuli into paler or greyish tones, giving the right and upper quadrants cooler greens, blues, and neutral grey AI models accurately identified graphite (C), pyrolusite (MnO_2), and other black pigments for mural outlines and shading in the lower-right quadrant. AI researchers can tell from this image if the AI-driven restoration found and restored original pigments or introduced unintended color shifts.

Figure 15. *Before and After Restoration Comparison of Mogao Grottoes Murals Using AI-Driven Color Reconstruction.*

Mogao Grottoes mural sections before and after AI-driven restoration are shown in Figure 15. The left mural section has significant pigment degradation from age, environmental exposure, and wear. The mural's faded colors, especially in intricate areas, show degradation. AI-reconstructed color on the right mural. AI deep learning models recreated missing pigments to match the historical color palette based on pigment data. The mural's color and depth are carefully restored. To match the original craftsmanship, we restored the color and refined the design. This comparison shows that AI-based restoration methods are more accurate, efficient, and scalable than manual ones. AI-driven mural conservation preserves history and art. This study shows that AI-driven spectral analysis and deep learning can revive Mogao Grottoes mural pigments. AI model used computer vision, color mapping algorithms, and spectral pigment analysis to identify and reconstruct historically accurate hues, ensuring restored mural sections matched their original artwork. By addressing manual retouching, subjective interpretation, and pigment instability over time, automated restoration methods can improve mural preservation accuracy, efficiency, and scalability. AI's ability to process large spectral datasets, predict missing pigment values, and precisely reconstruct mural sections may improve estimated pigment matching and artistic approximation restoration methods. Grid-based chromatic analysis and AI-predicted pigment classification demonstrate AI-driven restoration's scientific and reproducible potential, reducing the risk of inaccurate color restorations that could distort the Mogao Grottoes murals' historical AI-driven pigment classification accurately reconstructs mural tones with minimal deviation, according to statistical analysis. color mapping allowed AI to analyze pigment degradation patterns, distinguish between historically and non-historically used pigments, and reconstruct mural sections with their original chromatic composition. AI-based restoration models corrected color imbalances, faded pigment sections, and mural clarity on the soft-warm (S-W) and hot-cool (H-C) chromatic grid without artificial distortions or modern pigment approximations. AI-reconstructed pigment values match historical pigment values, proving deep learning-based spectral analysis works in mural conservation and emphasizing the need to integrate AI into large-scale digital heritage preservation projects. They also show that AI models trained on large spectral datasets of historical pigments can automate restoration with unprecedented accuracy, emphasizing the need for data-driven cultural heritage conservation [31,32].

AI can restore mural pigments using hue shift analysis and contrast enhancement. AI used deep learning brightness and contrast adjustments to find, classify, and reconstruct mural pigments. AI corrects pigment spectral distortions from oxidation, mineral transformation, and environmental exposure. AI models can improve pigment accuracy by adjusting hue (+90, -90, ±180) to correct chromatic inconsistencies, recover faded elements, and reconstruct mural sections using historical pigment compositions. AI can predict and reconstruct missing hues using spectral reflectance data, replacing subjective, history-bound manual restoration [33,34].The comparison between original and AI-restored mural sections shows that AI can accurately replicate lost pigments, reconstruct damaged sections, and seamlessly blend restored elements with mural compositions. AI identified preserved pigments and corrected faded sections to improve mural vibrancy and clarity using grid-based color distribution analysis. AI-driven restoration models can recreate mural pigments with near-exact spectral values, preserving history. Machine learning is a scalable, scientifically-based restoration method that outperforms conventional methods in accuracy, efficiency, and reproduction by preserving mural depth, texture, and artistic essence while eliminating degradation and pigment loss [35,36]. Comparison of AI-predicted and historical pigments shows deep learning can recreate mural colors. Most reconstructed pigments had good spectral consistency, with AI-predicted hues matching historical pigments. AI-based restoration matches mural pigments' historical compositions with minimal spectral deviation, preserving their artistic and scientific integrity. Pigment estimation errors, manual retouching limitations, and environmental degradation hampered previous restoration attempts, but this accuracy improves automated digital heritage conservation. Mural sections with natural pigment degradation require AI to accurately reconstruct unstable and chemically transformed pigments. Deep learning-based pattern recognition and historical pigment datasets helped AI models predict and reconstruct missing spectral values in degraded sections. AI must regenerate pigments and stabilise chemical changes to preserve murals. AI can detect, classify, and reconstruct unstable pigments using spectral analysis and historical pigment references, making it essential for digital conservation. Data reduces mural restoration errors [2, 37].Machine learning models accurately reconstruct ancient murals, paintings, and other cultural artefacts using large pigment datasets, demonstrating the wider implications of AI-based restoration in digital heritage conservation. AI can automate restoration while preserving historical authenticity, making it a scalable and efficient alternative to manual conservation, which takes time, expertise, and human intervention. AI-assisted restoration may help museums, researchers, and conservationists reconstruct, preserve, and digitally archive ancient artworks, according to a study. Pigment analysis on Mogao Grottoes murals trains machine learning models for color reconstruction, spectral prediction, and digital conservation in future AI-based restoration research [3,38]. Mogao Grottoes mural pigment preservation, reconstruction, and enhancement accuracy and efficiency are improved by deep learning models, spectral imaging, and automated pigment classification. AI can reconstruct faded mural sections, compare AI-predicted pigments to historical pigments, and improve hue and contrast for cultural heritage conservation. AI-driven restoration preserves ancient art without altering composition. This research prepares AI-based conservation initiatives using machine learning and spectral analysis to preserve cultural heritage beyond Mogao Grottoes. AI-driven system was used in different application in literature [39-45].

5. Conclusions

Computer vision, deep learning, and spectral analysis restored Mogao Grottoes mural colors. Scientific, scalable heritage conservation is possible. AI-based restoration used convolutional neural networks, pattern recognition algorithms, and historical pigment datasets to analyse degraded mural sections, identify pigment loss patterns, and reconstruct missing colors more accurately and efficiently than manual restoration. Deep neural networks trained on spectral reflectance data, historical pigment compositions, and environmental degradation models reconstructed lost hues with minimal mural color deviation and created a standardised digital pigment database for reproducible and scientifically validated restoration in large-scale cultural Artificial intelligence, high-resolution spectral imaging, and expert validation improve color reproduction, ensuring digitally restored murals match their historical compositions and eliminating pigment interpretation and artistic approximation biases.This study suggests that scientifically standardised AI-driven pigment classification using spectral color mappings, historical pigment records, and expert assessments can improve mural restoration. AI-based hue shift adjustments, brightness and contrast optimisation, and pigment classification algorithms ensure that reconstructed pigments match their original spectral values and maintain structural integrity in relation to adjacent mural sections, preventing inconsistencies from isolated restoration attempts. Machine learning models trained on large pigment datasets can reconstruct mural colors that reduce degradation, oxidation, and fading. AI-predicted pigment values match historical compositions.The research also shows that machine learning models can process high-resolution mural scans, detect spectral inconsistencies, and apply targeted restoration algorithms without manual intervention, improving restoration efficiency and reproducibility across multiple cultural heritage sites. AI's ability to accurately reconstruct unstable or chemically transformed pigments suggests that deep learning models can predict missing spectral information to restore mural sections with irreversible pigment changes from environmental exposure and chemical interactions. In the study, AI-based restoration improved color accuracy, mural depth, texture, tonal balance, artistic and historical integrity. This research alters cultural heritage preservation, reconstruction, and digital preservation for future generations. Deep learning could be used in large-scale mural conservation projects to preserve ancient artworks with scientific precision after this study shows that AI can systematically reconstruct lost pigments with high spectral accuracy while maintaining historical authenticity. A standardised digital pigment database for AI-assisted restoration helps conservators restore more accurately and reproducibly by eliminating subjective interpretation and manual color approximation inconsistencies. In this AI-driven mural restoration method, deep learning models, spectral imaging, and historical pigment analysis improve digital heritage preservation accuracy, efficiency, and scalability.

5.1. Limitation & Future Recommendations:

Though successful, this finding has limitations. Many ancient pigments have deteriorated over centuries, making AI's reconstruction difficult. AI models may struggle to simulate oxidation, light, and chemical pigment appearance changes. AI-generated colors may differ from ancient artists' intent, raising ethical concerns about artistic integrity and historical authenticity in cultural heritage conservation. AI predictions without expert validation may introduce subtle biases, emphasizing the need for human oversight in all restoration decisions. Future research should use GANs and transformer-based architectures to improve color predictions and AI-driven restoration. Additionally, applying AI restoration methods to other cultural heritage sites beyond the Mogao Grottoes will validate the method in different historical contexts. AI models should be improved by archaeologists, art historians, and material scientists using archaeological pigment studies, multispectral imaging, and pigment ageing simulations.

5.2. Implications

This study affects digital heritage conservation, AI-driven restoration, and technology-cultural preservation partnerships. Using data-driven and standardized methods, the study reconstructs faded and missing pigments in historical murals more accurately and efficiently than traditional restoration methods. This research uses computer vision, deep learning, and spectral pigment analysis to restore historical artworks beyond the Mogao Grottoes, preserving global heritage. AI models can analyse pigment compositions, detect ageing patterns, and reconstruct colors without human intervention, making them scalable and suitable for ancient frescoes, traditional paintings, and architectural decorations. This research reduces manual restoration time, cost, and subjectivity by improving workflow efficiency and reproducibility

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