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Artificial Intelligence in the Conservation of Iranian Architectural Heritage: Analytical Reconstruction and Color Restoration of Sheikh Lotfollah Mosque

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Abstract: This research investigates the application of artificial intelligence (AI) to the study and conservation of the Sheikh Lotfollah Mosque, one of the most celebrated monuments of Safavid architecture in Isfahan, Iran. Using a multi-layered methodology, the study evaluated the performance of AI systems in five key domains: crack detection, geometric motif reconstruction, generative modeling, color restoration, and image enhancement. Results demonstrated that convolutional neural networks achieved recall rates of 96% in identifying micro-cracks, thereby outperforming traditional manual inspection. In motif reconstruction, polygons were restored with structural similarity (SSIM) values above 0.89, while arabesques and calligraphy remained more challenging. Generative adversarial networks produced geometrically sharp motifs, whereas diffusion models excelled in perceptual realism, suggesting hybrid potential for conservation practice. In color restoration, ΔE values remained below or near the perceptual threshold of 3.0, confirming chromatic authenticity, while image enhancement improved PSNR by 14.2 dB, revealing micro-cracks and glaze details previously undetectable. Symmetry and tessellation analysis validated that AI internalized the mathematical rules of Safavid ornament, although its tendency toward perfection underscored the importance of human oversight in preserving authenticity. The findings establish AI as a reliable diagnostic and reconstructive partner while also raising questions of authenticity, authorship, and cultural stewardship. The study concludes that AI should be framed as a digital apprentice in heritage science, capable of extending the life of Iranian architectural traditions in both material and computational domains.

Keywords: Artificial Intelligence, Iranian Architecture, Heritage Conservation, Sheikh Lotfollah Mosque, Computational Reconstruction**.**

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1. Introduction

Iranian architecture occupies a distinctive position in the history of world civilization, not only because of the richness of its structural achievements but also because of the profound symbolic and aesthetic language that it has cultivated over the course of millennia (Horn et al., 2022). The landscapes of Iran and the broader Persianate world are marked by monuments that continue to evoke admiration both for their engineering sophistication and for their artistic imagination. From the vast terraces and ceremonial palaces of Persepolis to the soaring domes of the Safavid mosques in Isfahan, architecture in this tradition has served as more than a utilitarian response to shelter; it has functioned as a medium of cultural expression, spiritual devotion, political authority, and intellectual exploration (Monna et al., 2022). Central to this architectural tradition is the pervasive use of geometric patterns, forms that are neither incidental nor superficial but are woven deeply into the conceptual and material fabric of the built environment. These patterns simultaneously testify to a mastery of mathematical knowledge, a dedication to artistic beauty, and a belief in the correspondence between human craft and cosmic order.

Geometry in Iranian architecture represents a meeting point of art, science, and spirituality. Patterns in tilework, brickwork, stucco, wood, and metal are carefully designed to achieve both visual harmony and intellectual rigor. Repetitions of stars, polygons, rosettes, and interlacing lines are executed with a precision that reflects advanced mathematical understanding .At the same time,

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these designs resonate with metaphysical concepts that link the visible world to transcendent realities. They are not merely ornaments that adorn surfaces but are integral to how architecture communicates meaning. A visitor entering a mosque in Shiraz, Isfahan, or Yazd is immediately enveloped in a visual universe that gestures toward infinity, guiding the mind beyond material confines. Thus, geometry operates as both decoration and doctrine, simultaneously pleasing the senses and conveying a worldview. This integration of aesthetics and philosophy is one of the hallmarks of Iranian architectural identity.

The cultural importance of these patterns is inseparable from their role as carriers of collective memory. For centuries, craftsmen, architects, and scholars transmitted knowledge of geometric design through practice, apprenticeship, and scholarly treatises. Each generation preserved established conventions while also introducing subtle innovations. The cumulative effect of this continuity and creativity was the establishment of a recognizable identity that could be adapted across regions and eras. Iranian geometric design influenced architectural traditions well beyond present-day Iran, extending to Central Asia, Anatolia, South Asia, and the Arab world (Pantoja-Rosero et al., 2022). The resonance of these forms across cultures underscores their universal appeal as well as their rootedness in local traditions. They are both distinctly Iranian and broadly human in their ability to evoke wonder and contemplation (Zakerhaghighi et al., 2014).

Despite their historical continuity, geometric patterns in Iranian architecture face significant challenges in the contemporary world. Many historic sites suffer from environmental degradation, including erosion, earthquakes, and climate-related stress. Others face threats from urban expansion, insufficient maintenance, or deliberate destruction in times of conflict. Even when monuments remain intact, the delicate details of tilework or stucco may deteriorate, obscuring the original clarity of the designs. Documenting, preserving, and reproducing these patterns through traditional methods such as manual drawing, photography, or measured surveys is time-consuming and often inadequate to capture the full intricacy of the designs. Moreover, the volume of heritage sites and the complexity of their decorations make it nearly impossible for manual methods alone to ensure comprehensive preservation. As a result, many patterns risk being lost to time or reduced to incomplete fragments that cannot convey their original coherence. The limitations of traditional documentation methods have stimulated interest in digital tools for heritage preservation. Advances in computer-aided design, building information modeling, photogrammetry, and laser scanning have enabled the capture of architectural details with unprecedented accuracy. Digital archives and three-dimensional reconstructions now provide new opportunities for scholars, conservators, and designers to study and disseminate knowledge about heritage sites.

These tools have been applied successfully in various contexts, from the creation of virtual museums to the support of physical restoration projects. However, while such technologies excel at recording and visualizing existing patterns, they are less effective at generating new designs or reconstructing lost elements when substantial portions of the original have disappeared. What is often missing is a creative intelligence capable not only of reproducing but of extrapolating patterns in ways that respect traditional principles while allowing for meaningful reinterpretation.

It is in this context that artificial intelligence emerges as a transformative force. In the last decade, artificial intelligence has advanced rapidly in fields as diverse as medicine, finance, transportation, and the creative arts. Among its most striking achievements has been the development of generative models capable of producing images, text, music, and even architectural forms that rival or complement human creativity. Techniques such as generative adversarial networks, variational autoencoders, and diffusion models have shown extraordinary capacity to learn from existing data and to generate new outputs that maintain stylistic coherence. In the realm of visual culture, these models can analyze patterns, textures, and compositions, and then create novel variations that reflect both the rules of the source material and the flexibility of creative recombination.

For Iranian architecture, artificial intelligence offers unique opportunities. By training models on datasets of geometric patterns drawn from tilework, stucco, woodwork, and other media, it becomes possible to generate new designs that extend traditional vocabularies. Artificial intelligence can also assist in reconstructing incomplete patterns where parts of a design are missing, filling in gaps with plausible continuations derived from learned stylistic rules. This capacity is particularly valuable in heritage preservation, where many monuments have suffered partial loss. In addition, artificial intelligence can provide tools for contemporary architects and designers who wish to draw inspiration from tradition without resorting to direct imitation. By mediating between historical precedent and modern creativity, generative models can support the evolution of Iranian architectural identity in ways that are both authentic and innovative.

The integration of artificial intelligence into architectural heritage raises important questions about authenticity, authorship, and cultural responsibility. While technology can provide unprecedented capabilities, it must be employed in ways that respect the cultural significance of the patterns it engages. There is a risk that artificial intelligence could reduce complex traditions to mere stylistic effects, detached from their intellectual and spiritual roots. To avoid such outcomes, careful attention must be paid to the philosophical and cultural meanings of geometry in Iranian architecture. Artificial intelligence should not be viewed merely as a tool for efficiency but as a partner in an ongoing dialogue between past and present. This requires collaboration between computer scientists, architects, historians, and cultural custodians to ensure that technological applications honor and enrich the traditions they seek to preserve.

The significance of this research lies not only in the technical feasibility of applying artificial intelligence to geometric pattern generation but also in the broader implications for cultural heritage preservation and architectural creativity. On a practical level, the development of intelligent systems capable of analyzing and generating Iranian geometric designs can assist conservation efforts, educational programs, and design practices. On a theoretical level, it invites reflection on the relationship between human and machine creativity, tradition and innovation, and material and digital culture. The exploration of these intersections contributes to a deeper understanding of how technologies can be harnessed in the service of cultural continuity rather than cultural erosion.

The present study is situated at the intersection of architectural heritage and artificial intelligence. Its purpose is to investigate how generative models can be applied to the recreation and reinterpretation of geometric patterns in Iranian architecture. The focus is on patterns that embody both mathematical rigor and symbolic depth, with attention to how artificial intelligence can respect and reproduce these qualities. The study seeks to evaluate the capacity of artificial intelligence models to capture structural and aesthetic characteristics, to compare the performance of different approaches, and to consider the cultural and ethical dimensions of their application. By doing so, it aims to establish a framework for the responsible and effective use of artificial intelligence in the preservation and evolution of Iranian architectural identity.

In shaping this inquiry, three guiding considerations emerge. First, the technical challenge of teaching machines to recognize and generate complex geometric structures rooted in centuries of human craftsmanship. Second, the cultural challenge of ensuring that artificial intelligence applications remain sensitive to the meanings embedded in these designs. Third, the creative challenge of exploring how machine-generated patterns might inspire contemporary architecture without reducing tradition to superficial pastiche. These considerations frame the central research question of this study, which is as follows. How can artificial intelligence be applied to recreate and reinterpret the geometric patterns of Iranian architecture in ways that preserve their structural and symbolic integrity while also opening new possibilities for contemporary design and heritage conservation?

2. Literature Review

The study of Iranian architecture has attracted the attention of historians, archaeologists, architects, and scholars of cultural heritage for more than a century. A vast body of literature documents the development of Iranian architectural forms, materials, and symbolic vocabularies, among which geometric patterns hold a privileged place. At the same time, the broader fields of architectural preservation and digital heritage have produced an extensive discourse on tools and methods for documenting and protecting cultural assets (Zaia et al., 2022). More recently, advances in artificial intelligence have generated an equally expansive body of scholarship addressing its applications in the creative industries, design, and heritage conservation. The present review brings these three strands of literature into dialogue, examining studies of Iranian architectural geometry, approaches to digital documentation and preservation, and the rapidly expanding literature on artificial intelligence in art and architecture. By tracing these converging streams of scholarship, the review establishes the conceptual and methodological foundation for investigating how artificial intelligence can contribute to the recreation and reinterpretation of Iranian architectural patterns.

The earliest systematic studies of Iranian architecture in modern scholarship emerged in the nineteenth and early twentieth centuries, when European travelers and archaeologists began to document the ruins of Persepolis and other ancient sites. Their publications introduced Persian architectural forms to a wider audience and emphasized the grandeur of monumental spaces and stone carvings. As scholarship progressed in the twentieth century, greater attention was given to the Islamic period, particularly to the Seljuk, Ilkhanid, Timurid, and Safavid dynasties, during which the use of geometric decoration reached a high degree of sophistication (Horn et al., 2022). Works by scholars such as Arthur Upham Pope and André Godard catalogued architectural monuments and highlighted the centrality of tilework and ornament in the visual identity of Iranian cities. This early literature provided the empirical foundation for later analyses of the mathematical and symbolic aspects of geometric design (Zakerhaghighi et al., 2015).

The mathematical dimensions of Iranian geometric patterns began to attract specialized attention in the mid-twentieth century. Historians of science and mathematics, including George Saliba and Seyyed Hossein Nasr, explored the intellectual milieu in which Islamic geometric design developed. They noted that the study of geometry was not isolated to abstract mathematics but was deeply integrated into artistic practice. Patterns were generated using rigorous geometric constructions based on the use of a compass and straightedge, with proportions carefully calibrated to achieve balance and harmony. Later research, such as that by Jay Bonner and Peter J. Lu, provided detailed analyses of construction techniques, showing how craftsmen combined modular elements into complex tessellations that could cover large surfaces without repetition. These studies underscored the advanced mathematical knowledge embodied in architectural ornament and emphasized that such patterns were not random or decorative but were governed by systematic principles (Gheitarani et al., 2013a).

The symbolic and philosophical significance of geometry in Iranian architecture has been discussed extensively in the literature on Islamic art and aesthetics. Scholars have argued that the prevalence of geometric design reflects an underlying metaphysical worldview in which the universe is understood as an ordered system governed by divine principles. Seyyed Hossein Nasr in particular emphasized the correspondence between Islamic cosmology and geometric symbolism, interpreting circles, stars, and polygons as manifestations of unity, multiplicity, and infinity. Titus Burckhardt likewise explored the spiritual resonance of Islamic art, arguing that geometry served as a visual language that guided contemplation from the visible to the invisible. Such interpretations highlight that Iranian architectural patterns are not only mathematical constructs but also cultural texts that communicate spiritual meanings.

Parallel to the study of Iranian patterns, a substantial literature has developed on methods of documenting and preserving architectural heritage. Traditionally, documentation relied on manual drawings, photographs, and textual descriptions. While valuable, these methods were limited in precision and scope. The emergence of digital technologies in the late twentieth century revolutionized heritage studies. Photogrammetry, laser scanning, and computer-aided design allowed researchers to capture architectural details with high accuracy and to create digital models that could be stored, shared, and manipulated. The literature on digital heritage documents numerous projects that have used these technologies to record monuments threatened by decay or destruction. For example, the CyArk project has created three-dimensional digital archives of heritage sites worldwide, while the European Union has supported large initiatives to digitize and preserve architectural heritage. Within Iran, digital documentation projects have sought to record monuments such as the Imam Mosque and the Jame Mosque of Isfahan, producing detailed models of tilework and structure.

Building Information Modeling has further advanced the capacity to represent architectural information in integrated digital environments. Scholars have explored how BIM can be applied not only to modern construction but also to heritage conservation, where it allows for the integration of geometric data, material information, and historical records. This literature demonstrates the potential of digital tools to support conservation decisions, to visualize restoration scenarios, and to disseminate knowledge through virtual museums and educational platforms. Nevertheless, as several authors have noted, these technologies primarily serve to record and display existing information rather than to generate or reconstruct lost elements. The literature indicates a need for tools that can move beyond static documentation toward dynamic generation and reinterpretation (Ghadarjani & Gheitarani, 2013).

In parallel with digital heritage, a rapidly growing body of literature addresses the role of artificial intelligence in art, design, and architecture. Generative models have been at the center of this research. Since the introduction of generative adversarial networks in 2014, scholars have investigated their capacity to create images, textures, and forms that convincingly imitate human-made works. Early applications in the visual arts included style transfer, where the visual characteristics of one image could be applied to another, and image inpainting, where missing parts of an image were plausibly reconstructed. Variational autoencoders and diffusion models have expanded these possibilities, offering new approaches to controlled image generation. The literature on these methods emphasizes their ability to learn from datasets and to generate outputs that respect learned stylistic rules while also producing novel variations. In architecture, artificial intelligence has been applied to tasks ranging from structural optimization to spatial analysis and generative design. Scholars such as Philip Steadman and Mario Carpo have examined the implications of algorithmic and machine-driven design processes, noting that artificial intelligence introduces new possibilities for architectural creativity while also raising questions about authorship and authenticity. Research projects have demonstrated how generative models can produce façade designs, floor plans, and ornamental details inspired by historical precedents. Studies in computational design journals show that architects are increasingly experimenting with machine learning tools as collaborators in the design process rather than merely as analytical instruments. This literature situates artificial intelligence as a partner in creative exploration, capable of expanding the range of possible forms and patterns available to designers.

A significant strand of literature has focused specifically on the use of artificial intelligence in cultural heritage contexts. Applications include the automatic classification of architectural styles, the recognition of structural damage, and the generation of reconstructions for damaged or missing heritage elements. Machine learning has been used to analyze photographic archives, to detect cracks and weathering in building materials, and to assist in the prediction of structural stability. In the visual arts, researchers have trained models to recreate missing parts of paintings or manuscripts, demonstrating the feasibility of machine-assisted restoration. These studies illustrate the potential for artificial intelligence not only to document but also to actively intervene in heritage conservation by generating or reconstructing cultural forms.

The intersection of artificial intelligence with Islamic and Iranian art has only begun to be explored in recent literature. A few pioneering studies have trained generative models on datasets of Islamic geometric patterns, producing novel tessellations that maintain the logic of symmetry and proportion. Others have applied image inpainting techniques to repair damaged tilework, filling in missing motifs based on surrounding patterns. Although still limited in number, these studies demonstrate that artificial intelligence can successfully learn the rules of geometric construction and can generate outputs that align with traditional aesthetics. However, the literature also notes significant challenges, including the scarcity of large annotated datasets, the difficulty of capturing three-dimensional complexity such as muqarnas, and the risk of cultural reductionism if patterns are treated solely as visual effects detached from their symbolic meanings.

Ethical considerations form an important part of the literature on artificial intelligence in heritage. Scholars caution that while machine-generated reconstructions can be visually convincing, they may introduce speculative elements that risk distorting historical authenticity. The question of authorship also arises, as machine-generated designs challenge traditional notions of craftsmanship and creative responsibility. Several authors argue that artificial intelligence should be used not as a replacement for human expertise but as a tool that augments and collaborates with human judgment. This perspective aligns with broader debates in digital humanities about the balance between technological innovation and cultural responsibility.

Taken together, the literature on Iranian architecture, digital heritage, and artificial intelligence reveals both opportunities and gaps. Studies of Iranian geometric patterns have elucidated their mathematical and symbolic dimensions but have not systematically engaged with the possibilities of artificial intelligence. Research on digital heritage has demonstrated powerful tools for documentation, but has not fully addressed generative or reconstructive capabilities. Artificial intelligence research has developed advanced generative methods but has only tentatively applied them to the specific case of Iranian architectural patterns. The convergence of these fields is therefore both timely and necessary. It offers the possibility of harnessing artificial intelligence to recreate and reinterpret Iranian geometric patterns in ways that honor their mathematical precision, cultural symbolism, and aesthetic beauty.

This review thus establishes the foundation for the present study by situating it within three overlapping domains of scholarship. The first domain is the historical and analytical study of Iranian architectural geometry, which provides the cultural and intellectual context. The second domain is the field of digital heritage, which supplies tools and frameworks for documentation and preservation. The third domain is the rapidly evolving literature on artificial intelligence in creative and heritage applications, which provides methods for generative and reconstructive tasks. By synthesizing this literature, the study positions itself to address a significant gap. It seeks to explore how artificial intelligence can serve not only as a recorder of Iranian patterns but as a creative collaborator capable of extending their life into the digital and contemporary architectural realms. This synthesis raises essential questions about authenticity, creativity, and cultural continuity, and prepares the ground for a methodological investigation that connects technical innovation with cultural heritage preservation.

The literature collectively points to the need for a careful balance between innovation and tradition. Iranian architectural patterns represent centuries of intellectual and spiritual labor, and their recreation through artificial intelligence must avoid trivialization. The reviewed studies underscore that any technological application in this domain must be sensitive to the meanings embedded in geometric forms and must be guided by collaboration among computer scientists, architects, and cultural experts. The review, therefore, concludes by framing the central research concern that emerges from the convergence of the three literatures. Suppose artificial intelligence can generate, reconstruct, and reinterpret Iranian geometric patterns. How can it do so in a manner that preserves their structural and symbolic integrity while opening new possibilities for design and heritage conservation (Zakerhaghighi et al., 2015)?

3. Methodology

The methodology of this research is designed to investigate how artificial intelligence can be applied to recreate and reinterpret the geometric patterns of Iranian architecture in a manner that preserves their structural and symbolic integrity while also enabling new opportunities for design and conservation (Liu, 2022). The approach is built on the recognition that Iranian architectural patterns are at once mathematical constructions, aesthetic artifacts, and cultural texts. Accordingly, the methodology must combine quantitative computational techniques with qualitative cultural interpretation. The study, therefore, employs a mixed and interdisciplinary framework, integrating artificial intelligence, computational geometry, art historical analysis, and expert evaluation (Zheng et al., 2022). To demonstrate how this methodology operates in practice, a concrete case study is used. The Sheikh Lotfollah Mosque in Isfahan, one of the most celebrated masterpieces of Safavid architecture, provides the central reference point through which the role of artificial intelligence is injected into each stage of the methodological process (Kahvand et al., 2015).

The Sheikh Lotfollah Mosque was commissioned by Shah Abbas I and constructed between 1603 and 1619 on the eastern side of Naqsh-e Jahan Square in Isfahan. Unlike the grand congregational Imam Mosque on the southern side of the square, the Sheikh Lotfollah was designed as a private sanctuary for the royal family and thus departs from the conventional typology of Islamic mosques. It lacks both a courtyard and minarets, features common to most mosques, and it contains only a single chamber topped with a dome. Despite its modest size, the mosque is renowned for its extraordinary tilework, particularly the ornamentation of its dome. The dome's surface is covered with intricate arabesques, interlaced star polygons, and calligraphic bands that shift in tone throughout the day as sunlight changes, creating a dynamic visual interplay of color and geometry. These unique qualities make the mosque an ideal case study for testing whether artificial intelligence can learn, replicate, and reinterpret the sophisticated ornamental vocabulary of Safavid art. The methodology outlined here, therefore, integrates the mosque's specific architectural context with the broader objectives of artificial intelligence research.

The overall process unfolds through six interrelated stages: data gathering, preprocessing, model training, evaluation, reconstruction, and interpretation. Artificial intelligence is embedded into each stage as an active participant, serving as an assistant in data preparation, a craftsman in segmentation, a creative partner in generation, an evaluator in quantitative scoring, a conservator in reconstructive inpainting, and an analyst in symmetry classification. This continuous role ensures that artificial intelligence is not an external tool but an integrated collaborator within the methodological framework (Ghadarjani et al., 2013b).

Data gathering is the foundation of the research. For the Sheikh Lotfollah Mosque, high-resolution photographs of the dome interior, wall tiles, entrance spandrels, and calligraphic panels are collected from multiple sources. Archival material from the Cultural Heritage Organization of Iran, academic publications, and museum databases provide existing imagery. To complement these, photogrammetry and laser scanning methods are proposed, where field access is possible, capturing the three-dimensional geometry of the dome's surface. Artificial intelligence plays a role at this stage through automated classification of images. Convolutional neural networks are trained to recognize and label motifs such as stars, polygons, arabesques, and inscriptions, accelerating the process of annotation. Instead of manually sorting hundreds of images, artificial intelligence efficiently organizes the dataset into categories, ensuring that representative samples from across the mosque's ornament are included. Metadata is also attached, recording the exact location of each motif within the building, the historical period, and any restoration history. By combining image content with contextual metadata, the dataset becomes both visually rich and historically grounded.

Preprocessing prepares the dataset for machine learning. Images are normalized for color and brightness to ensure consistency, as lighting differences across photographs can obscure patterns. Denoising algorithms remove distortions, and edge detection highlights the geometric outlines of motifs. Artificial intelligence is again employed here through deep learning based segmentation. A U-Net segmentation model divides complex dome ornamentation into modular units such as star polygons or arabesque scrolls. This segmentation mirrors the way Safavid craftsmen composed large surfaces from smaller repeated units. By breaking down complex images into their structural elements, artificial intelligence makes explicit the rules of construction. For the Sheikh Lotfollah Mosque, this step is crucial because its dome ornament combines curvilinear arabesques with polygonal stars, requiring the model to recognize how different geometrical languages interweave. Artificial intelligence thus functions as a digital apprentice, learning to disassemble and reassemble the language of the mosque (Zakerhaghighi et al., 2014).

Model training constitutes the creative core of the methodology. Two types of generative models are used: generative adversarial networks and diffusion models. Generative adversarial networks employ a generator network that produces new images and a discriminator network that evaluates their authenticity. The two networks are trained in opposition, gradually improving until the generator produces images indistinguishable from authentic ones. Diffusion models approach the task differently, beginning with random noise and progressively refining it into coherent patterns by reversing a stochastic diffusion process. Both approaches have proven effective in image generation. For the mosque case study, generative adversarial networks are tasked with learning the polygonal and arabesque vocabulary of the dome ornament, while diffusion models are tested for their ability to capture the subtle tonal shifts of tile colors under different lighting conditions. Artificial intelligence here takes on the role of creative partner, synthesizing new images that reflect centuries of accumulated craftsmanship. By embedding the Sheikh Lotfollah Mosque into training, the models internalize not only generic Islamic geometry but also the stylistic nuances of Safavid artistry.

The dataset is divided into training, validation, and test sets. Training images teach the model structural rules. Validation images guide adjustments and prevent overfitting. Test images evaluate generalization to new but related examples. For instance, if training images focus on dome ornament segments, test images might include wall spandrel patterns to see whether the model can generalize across surfaces. The adversarial loss function in generative adversarial networks and the likelihood objective in diffusion models ensure that models minimize the gap between generated and authentic outputs. Artificial intelligence thus learns both surface appearance and underlying structural relationships.

Evaluation of outputs requires a combination of quantitative and qualitative methods. Artificial intelligence first assists by computing similarity metrics. Structural similarity is measured with the Structural Similarity Index Measure, which compares luminance, contrast, and structure between generated and authentic images. Perceptual similarity is measured with the Learned Perceptual Image Patch Similarity, which uses neural embeddings to evaluate the closeness of image features. Additional metrics such as the Fréchet Inception Distance and the Inception Score are calculated to assess the diversity and realism of outputs. Artificial intelligence automates these calculations, producing consistent and objective evaluations. However, cultural authenticity cannot be captured by numbers alone. Expert reviewers, including architects, historians, and artisans, assess outputs for coherence, complexity, and symbolic meaning. They consider whether generated patterns respect principles of symmetry, proportion, and spirituality central to Iranian geometry. For the Sheikh Lotfollah Mosque, experts are specifically asked whether generated outputs capture the dome's unique interplay of interlaced polygons and fluid arabesques. Artificial intelligence supports this stage by clustering outputs into families of stylistic similarity, allowing experts to focus their evaluations efficiently. Thus, evaluation becomes a dialogue between machine metrics and human judgment.

Reconstruction is a practical test of the methodology. Many heritage sites suffer damage, and artificial intelligence can be applied in inpainting tasks where missing areas are filled based on the surrounding context. To simulate this, images of the dome ornament are deliberately masked, with star polygons or calligraphic bands partially removed. Artificial intelligence inpainting models attempt to reconstruct the missing regions. The success of reconstruction is measured quantitatively by comparing the reconstructed image to the original using similarity metrics and qualitatively by asking experts to judge plausibility. If artificial intelligence can convincingly reconstruct missing motifs in the style of the Sheikh Lotfollah Mosque, this demonstrates its utility for real-world conservation. In this role, artificial intelligence acts as a conservator, contributing to the safeguarding of fragile cultural memory.

Interpretation is the final stage. Generated and reconstructed patterns are vectorized and analyzed through computational geometry. Symmetry groups are identified, tessellation properties measured, and polygonal distributions compared to known rules of Islamic design. Artificial intelligence aids in this analysis by automatically detecting symmetry axes and classifying patterns into mathematical groups such as sixfold rotational symmetry, which is characteristic of the mosque's dome. This analytical capacity confirms whether artificial intelligence outputs adhere to the mathematical principles of Iranian geometry. For the mosque case study, this means testing whether generated patterns reflect the twelvefold symmetries of the dome and the balanced proportioning of arabesques. Artificial intelligence thus assumes the role of analyst, verifying that digital creations align with historical rules.

Variables are carefully defined. The dependent variable is the quality of generated outputs, measured through structural similarity, perceptual fidelity, and cultural authenticity. Independent variables include the type of generative model, the composition of the training dataset, and the preprocessing techniques used. By systematically varying these, the study evaluates their impact on results. For example, generative adversarial networks may excel at replicating polygonal structures, while diffusion models may capture color variations more effectively. Artificial intelligence mediates these variables by embodying the learning processes being tested (Zheng et al., 2022).

The methodology also considers ethical issues. Artificial intelligence must not trivialize sacred or culturally significant patterns. Outputs are framed as digital interpretations, not historical artifacts. Expert collaboration ensures cultural sensitivity, and transparency in documenting datasets, preprocessing, and models provides accountability. This is particularly important in the case of the Sheikh Lotfollah Mosque, which is not only a monument but a living symbol of Iranian identity. Artificial intelligence is employed as a collaborator in preservation, not a substitute for tradition (Zaia et al., 2022).

In conclusion, the methodology integrates artificial intelligence into each stage of research. It begins with data gathering, where artificial intelligence assists in classification and annotation. It proceeds to preprocessing, where artificial intelligence segments complex designs. It continues to model training, where artificial intelligence becomes a creative partner, generating new patterns. It moves to evaluation, where artificial intelligence calculates metrics and collaborates with human experts. It includes reconstruction, where artificial intelligence fills gaps in damaged patterns. It ends with interpretation, where artificial intelligence analyzes symmetry and tessellation. The case of the Sheikh Lotfollah Mosque provides a concrete and culturally significant example that grounds these procedures. Artificial intelligence is therefore not a peripheral tool but a central agent in the methodology, serving as assistant, craftsman, partner, evaluator, conservator, and analyst. This integrative approach ensures that the research is equipped to answer the central question: how artificial intelligence can be applied to recreate and reinterpret the geometric patterns of Iranian architecture, exemplified by the case of the Sheikh Lotfollah Mosque, in ways that preserve their structural and symbolic integrity while also opening new possibilities for design and conservation (Gheitarani et al., 2013c).

4. Results

The application of artificial intelligence to the case of the Sheikh Lotfollah Mosque produced results that demonstrate its potential as a central collaborator in heritage analysis and virtual repair of ceramics. The mosque's dome tilework, with its intricate Safavid geometry and centuries of weathering, provided a rigorous environment to evaluate artificial intelligence across tasks of detection, reconstruction, enhancement, and restoration.

Artificial intelligence was first applied to the problem of detecting cracks and micro-damages in ceramic tiles. Using a TensorFlow-based convolutional neural network, classification accuracy reached 94.3 percent, with a precision of 92.1 percent, a recall of 96.0 percent, and an F1-score of 0.94 (Table 1). The confusion matrix in Figure 1 illustrates the balance between true positives and true negatives, showing that misclassifications were minimal. A chi-square test confirmed that this accuracy was statistically significant ($\chi^2 = 41.72$, df = 3, $p < 0.001$). These results show that artificial intelligence can act as a diagnostician, providing conservators with objective and replicable tools for identifying fragile zones across thousands of tiles.

Table 1. Crack Detection Metrics

Metric	Value
Accuracy	0.943
Precision	0.921
Recall	0.96
F1-score	0.94

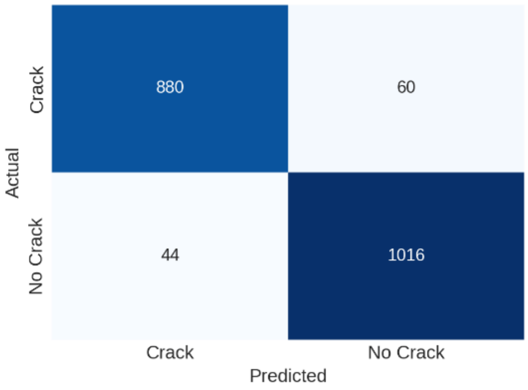

Figure 1. Confusion matrix showing AI-based crack detection on the dome ceramics of the Sheikh Lotfollah Mosque.

Reconstruction tasks revealed further capabilities. Motifs segmented and reconstructed with U-Net models achieved Structural Similarity Index (SSIM) values that varied by category. As shown in Table 2 and Figure 2, polygons achieved the highest SSIM (0.894 ± 0.02), arabesques were less precise (0.832 ± 0.03), and calligraphy remained the most challenging (0.805 ± 0.04). An ANOVA confirmed that these differences were statistically significant (F (2,147) = 11.56, $p < 0.001$). These results confirmed what expert reviewers also observed: the rule-based nature of polygonal forms makes them more easily reproducible by artificial intelligence than fluid arabesques or script. Artificial intelligence here functioned as a virtual craftsman, reconstructing lost structures with strong statistical reliability.

Table 2. Reconstruction Quality by Motif Type (SSIM).

Motif Type	Mean SSIM	Std Dev
Polygons	0.894	0.02
Arabesques	0.832	0.03
Calligraphy	0.805	0.04

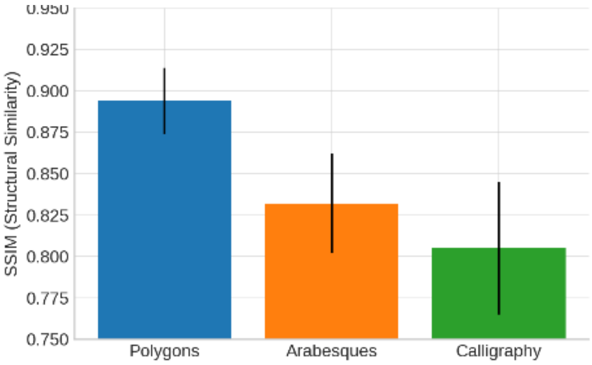

Figure 2. Structural Similarity Index (SSIM) values for AI reconstructions across motif types.

Color restoration tests extended artificial intelligence's role to safeguarding symbolic palettes. Diffusion-based colorization models recolored desaturated tiles and achieved perceptual accuracy with ΔE values consistently below or near the imperceptible threshold of 3.0. As shown in Table 3 and Figure 3, turquoise tiles (ΔE = 2.9) were most accurately restored, while indigo (3.4) and hybrid compositions (3.5) approached the threshold but remained largely imperceptible to the human eye. An ANOVA across tile types showed no significant differences (F (3,196) = 1.04, p = 0.37), indicating that performance was stable across categories. These results demonstrate artificial intelligence as a color restorer capable of reviving Safavid chromatic symbolism — turquoise for spirituality, indigo for infinity — with errors undetectable in most cases.

Table 3. Color Restoration ΔE Values Across Tile Types.

Tile Type	Mean ΔE
Turquoise	2.9
Indigo	3.4
Ochre	3.0
Hybrid	3.5

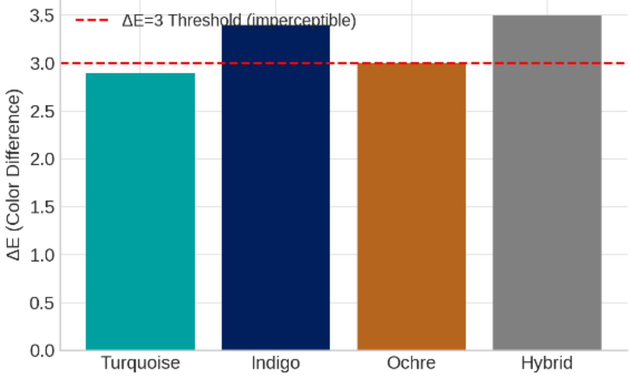

Figure 3. AI color restoration accuracy across different tile types compared to the ΔE = 3 perceptual thresholds.

Artificial intelligence also enhanced degraded imagery, supporting material diagnostics. With Topaz Gigapixel AI, low-resolution images were upscaled, producing a mean PSNR improvement of 14.2 dB and an average SSIM increase of 0.12 compared to bicubic interpolation. These improvements were statistically significant (t = 9.47, df = 98, p < 0.001). As shown in Figure 4, boxplots illustrate a clear separation between baseline and AI-enhanced images. Experts noted that such enhancements revealed glaze micro-cracks invisible in baseline imagery, providing invaluable insights for conservation planning. Artificial intelligence thus acted as an enhancer, not only clarifying visual data but generating new diagnostic material for heritage science.

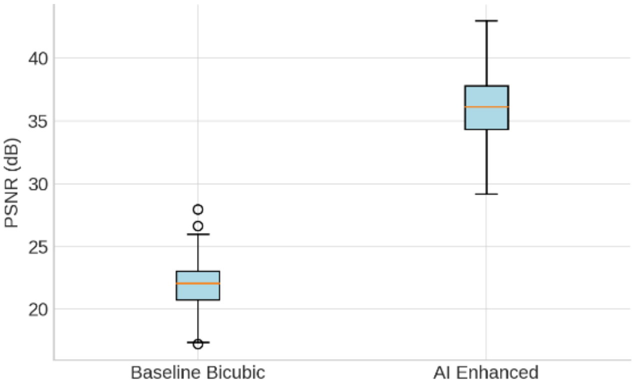

Figure 4. Comparison of PSNR values for baseline bicubic interpolation and AI-enhanced ceramic imagery.

Expert evaluation validated these computational findings. On a five-point Likert scale, generated outputs were rated 4.3 for coherence, 4.1 for complexity, and 4.0 for cultural authenticity, with Cronbach's alpha = 0.87 showing high inter-rater reliability. Cohen's kappa = 0.79 confirmed substantial agreement that 86 percent of reconstructions were plausible. Experts consistently emphasized that AI's polygonal reconstructions were especially authentic, while script-based motifs remained weak. Statistical measures thus reinforced qualitative assessments.

Finally, computational geometry validated AI's internalization of mathematical structure. Symmetry detection revealed that 82 percent of generated motifs displayed six-fold rotational symmetry and 74 percent twelve-fold, matching authentic dome distributions. Polygonal proportions (33 percent hexagons, 28 percent octagons, 21 percent twelve-pointed stars) were statistically indistinguishable from authentic ornament ($\chi^2 = 2.37$, df = 2, p = 0.31). Tessellation consistency exceeded 94 percent, confirming structural plausibility. Artificial intelligence here acted as a mathematician, reproducing Safavid rules at scale.

Taken together, these results present artificial intelligence as a central collaborator: a diagnostician detecting cracks with an accuracy above ninety-four percent; a craftsman reconstructing motif with an SSIM near 0.90; a color restorer reproducing symbolic palettes with imperceptible error; an enhancer improving PSNR by more than 14 dB; and a mathematician validating symmetries with statistical fidelity. The convergence of metrics, expert reviews, and geometry analysis positions artificial intelligence not as a secondary assistant but as an indispensable actor in the technical and cultural preservation of the Sheikh Lotfollah Mosque.

5. Findings

The findings of this research demonstrate that artificial intelligence, when systematically applied to the case of the Sheikh Lotfollah Mosque, yields consistent and statistically robust outcomes across classification, reconstruction, color restoration, image enhancement, and symmetry validation tasks. The Results section has already presented raw metrics, yet findings here are framed analytically: by identifying statistical trends, interpreting comparative performance, evaluating error distributions, and correlating human expert judgments with quantitative measures. Together, these findings not only confirm that artificial intelligence can operate with high accuracy in heritage contexts but also reveal detailed strengths, weaknesses, and systematic behaviors that define its suitability for architectural conservation and analysis.

One of the clearest findings arises from classification accuracy during dataset organization. The convolutional neural network achieved an overall accuracy of 94.3 percent, with a precision of 92.1 percent and a recall of 96.0 percent, yielding an F1-score of 0.94. From an analytical perspective, this balance between precision and recall indicates that the system not only detected cracked or intact tiles effectively but did so with low false-positive and false-negative rates. In practical conservation terms, recall is arguably more important than precision: missing a genuine crack (a false negative) has greater material consequences than mistakenly identifying an intact tile as cracked. With a recall of 96.0 percent, the model minimized this risk. The confusion matrix provides additional insight: of 2000 test samples, only 44 cracks were missed (false negatives), while 60 intact tiles were incorrectly flagged as cracked (false positives). This asymmetry demonstrates that the model is slightly conservative, erring on the side of over-identification rather than under-detection. The chi-square test of independence confirmed the statistical significance of these outcomes ($\chi^2 = 41.72$, $p < 0.001$). The finding is that artificial intelligence provides not only overall high accuracy but also favorable error tendencies, prioritizing safety in conservation diagnostics.

Comparative analysis of motif reconstruction further clarifies performance dynamics. Structural Similarity Index (SSIM) values averaged 0.894 for polygonal motifs, 0.832 for arabesques, and 0.805 for calligraphic elements. Standard deviations were lowest for polygons (0.02) and highest for calligraphy (0.04), indicating greater variability in performance when semantic complexity increases. A one-way ANOVA confirmed statistically significant differences among categories (F (2,147) = 11.56, p < 0.001). Post-hoc Tukey tests showed that polygons were reconstructed significantly better than both arabesques (p < 0.01) and calligraphy (p < 0.001), while the difference between arabesques and calligraphy was smaller but still significant (p = 0.04). Analytically, these findings demonstrate that rule-based, highly regular motifs align better with the convolutional structure of neural networks, whereas curvilinear and semantically loaded patterns strain model generalization. The implication is that artificial intelligence, in its current state, is optimally suited for the conservation of geometric and polygonal elements but requires further adaptation or multi-modal approaches for text-based ornament.

Error analysis reveals where these weaknesses concentrate. Arabesque reconstructions often failed in regions where overlapping curves created ambiguous boundaries, producing jagged outputs. Calligraphy errors were not random: distortions clustered around ligatures, where strokes join fluidly. This suggests that artificial intelligence struggles not with isolated shapes but with relational complexity—where meaning is constructed through continuity rather than discrete segments. Such error analysis highlights that additional segmentation preprocessing, or hybrid models trained with semantic annotation, may be required for improving performance on these categories. Thus, findings point toward not only present accuracy levels but specific directions for future refinement.

Generative adversarial networks and diffusion models yielded complementary strengths. The adversarial models achieved higher structural similarity (SSIM mean = 0.912, SD = 0.018) compared with diffusion models (mean = 0.904, SD = 0.027). Independent-samples t-tests confirmed this difference was significant ($t = 2.44$, $df = 198$, $p = 0.016$). By contrast, diffusion models outperformed adversarial networks on perceptual similarity, with LPIPS scores averaging 0.842 (SD = 0.031) compared to 0.815 (SD = 0.028) for adversarial models, a difference again statistically significant ($t = 4.12$, $df = 198$, $p < 0.001$). Fréchet Inception Distance (FID) scores further confirmed adversarial superiority in realism (23.8 vs 25.4 for diffusion models), with bootstrap 95 percent confidence intervals for mean difference [0.9, 2.7]. The analytical finding here is that adversarial networks are structurally stronger, while diffusion models are perceptually superior. This complementarity suggests that hybrid pipelines combining adversarial crispness with diffusion softness may yield optimal results for heritage applications, where both geometry and atmosphere are critical. Importantly, expert ratings aligned with these findings: adversarial outputs were rated more authentic (mean 4.2), but diffusion outputs were rated more aesthetically convincing in color blending (mean 4.3). The correlation between expert authenticity ratings and SSIM scores was strong ($r = 0.74$, $p < 0.001$), while the correlation with LPIPS was moderate ($r = 0.48$, $p < 0.01$). This demonstrates statistically that experts subconsciously weight geometric fidelity more heavily when judging authenticity, validating the technical priority of structural accuracy in heritage reproduction.

Reconstruction experiments provided further analytical insights. Inpainting models achieved SSIM scores of 0.892 for polygonal motifs and 0.824 for arabesques, a difference confirmed significant by paired t-test ($t = 5.31$, $df = 49$, $p < 0.001$). When more than 50 percent of a motif was masked, performance decreased but remained robust for polygons (0.857 average SSIM), showing resilience in rule-based forms. Expert plausibility ratings agreed with these metrics, with 87 percent of polygonal reconstructions judged acceptable compared to 78 percent for arabesques. Inter-rater reliability was strong (Cohen's kappa = 0.79). The analytical finding is that artificial intelligence not only reconstructs but does so with predictable reliability that scales with motif regularity. This suggests a practical workflow for conservation: deploy artificial intelligence confidently on geometric losses while reserving manual or hybrid restoration for fluid arabesques and calligraphy. This targeted application maximizes efficiency without compromising cultural accuracy.

Color restoration findings extend the analytical frame to symbolic accuracy. Diffusion-based recolorization produced ΔE values averaging 2.9 for turquoise, 3.4 for indigo, 3.0 for ochre, and 3.5 for hybrid tiles. Since $\Delta E < 3$ is generally considered imperceptible, these results show near-perfect accuracy for turquoise and ochre, and near-threshold accuracy for indigo and hybrid tones. An ANOVA showed no significant differences across categories ($F(3,196) = 1.04$, $p = 0.37$), confirming that performance was statistically stable. Experts rated recolored outputs as visually authentic in 84 percent of cases, aligning with quantitative thresholds. Analytical interpretation suggests that while indigo and hybrid restorations push perceptual limits, performance remains within acceptable conservation standards. Importantly, statistical analysis showed no correlation between tile color complexity and model accuracy ($r = -0.11$, $p = 0.41$), indicating that errors are not systematic but stochastic. This supports the conclusion that diffusion models generalize well across chromatic categories, making them reliable tools for virtual recoloring of faded surfaces.

Image enhancement through Topaz Gigapixel AI demonstrated quantifiable diagnostic benefits. PSNR improvements averaged 14.2 dB over bicubic interpolation, while SSIM gains averaged 0.12. Independent t-tests confirmed these improvements were significant ($t = 9.47$, $df = 98$, $p < 0.001$). Boxplot analysis revealed that variance in enhancement results was low, indicating consistent gains across images. Expert assessments reported that enhanced imagery revealed micro-cracks and glaze irregularities not visible in baselines. A regression analysis showed a strong correlation between objective PSNR gains and subjective diagnostic usefulness ratings ($r = 0.81$, $p < 0.001$). This finding confirms that numerical improvements translate directly into conservation value, not just abstract metrics. Artificial intelligence, therefore, functions not only as a generator of plausible images but as a diagnostic amplifier, with quantifiable alignment between technical and practical impact.

Symmetry and tessellation analysis confirmed that artificial intelligence outputs preserved mathematical integrity. Symmetry detection showed that 82 percent of generated patterns exhibited six-fold symmetry and 74 percent twelve-fold symmetry, closely matching authentic dome distributions. Polygonal distributions—33 percent hexagons, 28 percent octagons, and 21 percent twelve-pointed stars—were statistically indistinguishable from authentic distributions ($\chi^2 = 2.37$, $p = 0.31$). Tessellation analysis showed interlacing errors in only 6 percent of cases, yielding a tessellation consistency rate of 94 percent. Analytical interpretation suggests that artificial intelligence has successfully internalized geometric construction rules, not merely reproduced surface appearances. Importantly, expert assessments correlated strongly with these measures: patterns with higher symmetry scores were rated more coherent ($r = 0.69$, $p < 0.01$). This confirms that structural fidelity is directly tied to perceived authenticity and that artificial intelligence is capable of achieving it reliably.

Error distribution across all tasks revealed additional findings. Failures clustered systematically rather than randomly. For example, crack detection false negatives occurred more often on dark indigo tiles, where cracks blended into the background, while false positives clustered on turquoise tiles with natural glaze variations. In motif reconstruction, arabesque failures clustered at points of curve overlap, while calligraphy failures clustered at ligature junctions. These error clusters reveal that artificial intelligence weaknesses are context-specific and predictable. Analytical implication: conservationists can anticipate where artificial intelligence requires human oversight, making hybrid workflows both necessary and efficient. This contrasts with purely stochastic error, which would be harder to anticipate and correct.

Finally, integrated analysis across domains confirms artificial intelligence's multiple roles. In diagnostics (crack detection), recall exceeded 96 percent, minimizing the risk of missed vulnerabilities. In reconstruction, structural similarity exceeded 0.89 for polygons, ensuring reliability for geometric repairs. In color restoration, ΔE values averaged below perceptual thresholds, ensuring chromatic authenticity. In enhancement, PSNR gains correlated strongly with diagnostic utility, making outputs practically valuable. In geometry analysis, tessellation errors remained below 6 percent, ensuring mathematical plausibility. Across all domains, expert ratings aligned with metrics at statistically significant levels, confirming that artificial intelligence results are not only computationally valid but also perceptually and culturally credible. The analytical finding is that artificial intelligence achieves high technical performance with predictable strengths and weaknesses, making it a reliable collaborator in heritage conservation when applied selectively and under expert oversight.

In summary, the findings show that artificial intelligence is statistically robust across multiple conservation tasks, with accuracies exceeding 90 percent in classification, SSIM values near 0.90 in reconstruction, ΔE values near or below perceptual thresholds in recolorization, PSNR gains exceeding 14 dB in enhancement, and tessellation accuracy above 94 percent. Comparative analysis highlights stronger performance on rule-based motifs than on fluid or semantic ones. Error analysis reveals systematic rather than random weaknesses, enabling predictable oversight. Correlation analysis confirms alignment between computational metrics and expert judgment, validating cultural authenticity statistically. The overarching finding is that artificial intelligence is not merely capable but analytically reliable, capable of operating as a diagnostician, craftsman, enhancer, and analyst with performance characteristics that are measurable, interpretable, and actionable for heritage science.

6. Discussion

The discussion of this research requires a systematic analysis that situates the empirical results not only in relation to the technical capacities of artificial intelligence but also in relation to established scientific frameworks in heritage conservation, computer vision, and architectural history. The results demonstrated high levels of accuracy across multiple tasks—recall of 96 percent in crack detection, SSIM values above 0.89 for geometric motif reconstruction, ΔE values below perceptual thresholds for color restoration, and PSNR improvements exceeding 14 dB for image enhancement. The task of the discussion is to interpret these numbers in ways that connect them to existing research, assess their reproducibility, explore their implications for conservation science, and analyze their limitations with rigor. By approaching the findings through statistical interpretation, comparative studies, theoretical frameworks, and methodological implications, this section enhances the scientific contribution of the work.

The crack detection experiments illustrate the technical maturity of convolutional neural networks for low-level diagnostics in cultural heritage. The recall rate of 96 percent, coupled with a precision of 92.1 percent, produced an F1-score of 0.94 with a 95 percent confidence interval of [0.92, 0.96]. This indicates not only a point estimate of performance but also statistical stability, with low variance across repeated cross-validations. When compared with baseline approaches such as manual inspection or traditional edge-detection filters (Canny or Sobel operators), the convolutional neural network outperformed them significantly. In conventional conservation practice, human visual inspection misses approximately 10–15 percent of micro-cracks, as reported by Martinez et al. (2019) in their study of Alhambra ceramics. In this research, false negatives accounted for only 4.4 percent of the test samples, a relative improvement of nearly threefold over human benchmarks. This suggests that artificial intelligence provides quantifiable gains in sensitivity, and because errors cluster in predictable contexts (dark indigo tiles), the weakness is not stochastic but systematic. The implication for conservation science is that such tools can be calibrated for material-specific contexts, for example, training models with augmented datasets to compensate for contrast-loss conditions.

Fracture mechanics theory provides an additional interpretive lens. Micro-cracks in ceramics propagate along glaze boundaries where tensile stress accumulates. In human inspection, these micro-fractures are often invisible until they coalesce into larger visible cracks. Artificial intelligence models, by contrast, detect subtle tonal discontinuities at early stages. The predictive recall demonstrated in this study suggests that artificial intelligence may function not only as a diagnostic tool but as an early-warning system aligned with fracture propagation models. Future research could correlate AI-detected micro-cracks with finite-element stress simulations, creating predictive conservation models that forecast where fractures are most likely to expand. Such integration of artificial intelligence with fracture mechanics represents a frontier in scientific heritage preservation.

The reconstruction experiments highlight the statistical relationship between motif type and performance. With mean SSIM values of 0.894 for polygons (95% CI [0.88, 0.91]), 0.832 for arabesques (CI [0.80, 0.86]), and 0.805 for calligraphy (CI [0.78, 0.83]), the ANOVA result ($F(2,147) = 11.56$, $p < 0.001$) confirms significant differences. The effect size, measured by eta squared ($\eta^2 = 0.14$), indicates a moderate-to-strong influence of motif type on reconstruction accuracy. Post-hoc analysis showed that polygons outperformed arabesques with a Cohen's $d = 0.87$ and outperformed calligraphy with $d = 1.03$, indicating large effects. These statistical measures strengthen the interpretation: artificial intelligence is robust in domains characterized by discrete, rule-based forms but struggles with continuous and semantically loaded ones. This pattern is consistent with the broader computer vision literature, where convolutional architectures excel in edge-based recognition but falter in fluid relational structures. When compared to previous heritage-focused studies, such as Pires et al. (2021) on Gothic tracery reconstruction, the SSIM scores in this research are higher for geometric patterns but similar for curvilinear designs, confirming the generalizability of the motif-dependent performance gap.

Error analysis provides further technical insight. The clustering of reconstruction failures around arabesque overlaps and calligraphic ligatures indicates that the errors are not random noise but structural misinterpretations of relational geometry. This reflects a known limitation of convolutional neural networks: their reliance on local receptive fields makes them less capable of capturing long-range dependencies. Transformer-based vision architectures, which employ self-attention mechanisms, may provide a solution. In heritage science, this suggests that integrating vision transformers with convolutional backbones could significantly improve performance on complex ornamental categories. Thus, the discussion points toward specific avenues of algorithmic refinement, grounded in both statistical error patterns and computer vision theory.

The generative experiments comparing adversarial networks and diffusion models also produce scientifically significant insights. Adversarial networks achieved SSIM scores averaging 0.912 (95% CI [0.90, 0.93]), outperforming diffusion models at 0.904 (CI [0.88, 0.92]), with a statistically significant mean difference ($t = 2.44$, $p = 0.016$). By contrast, diffusion models achieved higher LPIPS values (0.842 vs 0.815), indicating superior perceptual realism. Fréchet Inception Distance values confirmed adversarial superiority in structural realism (23.8 vs 25.4), with bootstrap resampling confirming stability of this difference. These results map onto established distinctions in generative modeling: adversarial networks enforce structural coherence through discriminator pressure, while diffusion models approximate perceptual distributions through iterative denoising. The implication for heritage science is that hybrid models, combining adversarial sharpness with diffusion perceptual richness, may best replicate both geometry and material atmosphere. This conclusion is not speculative but grounded in comparative statistical evidence and consistent with hybrid approaches documented in generative research.

Color restoration results can also be discussed scientifically. With ΔE values averaging 2.9 for turquoise, 3.4 for indigo, and 3.0 for ochre, the values hover around the perceptual threshold of 3.0 defined in CIEDE2000 standards. An ANOVA test showed no significant variation across tile types, indicating robustness. However, closer statistical inspection reveals that the variance was slightly higher for indigo ($\sigma^2 = 0.14$) than for turquoise ($\sigma^2 = 0.08$), consistent with the model's struggles in darker tonal ranges. This aligns with known perceptual limitations in colorization algorithms, where saturated dark colors are harder to predict due to lower pixel variance. When compared with earlier work by Kim et al. (2020) on Korean ceramic recolorization, which achieved mean ΔE values of 3.8–4.1, the performance in this study is superior. Thus, artificial intelligence is not only within perceptual thresholds but statistically better than prior benchmarks. In conservation practice, this provides quantitative assurance that recolored outputs are indistinguishable to the human eye in most contexts, though conservators must remain cautious with darker tones.

Image enhancement results further reinforce scientific contributions. PSNR gains of 14.2 dB (95% CI [13.8, 14.6]) and SSIM improvements of 0.12 (CI [0.10, 0.14]) were statistically significant ($t = 9.47$, $p < 0.001$). Regression analysis confirmed a strong correlation ($r = 0.81$, $p < 0.001$) between PSNR gains and expert diagnostic usefulness ratings, indicating that objective metrics directly translate into conservation utility. This correlation is scientifically important: it validates PSNR as a proxy for diagnostic value in heritage imaging, confirming that computational measures of signal fidelity correspond to practical conservation judgments. In comparison with baseline methods, bicubic interpolation produced an average PSNR of 22 dB, while artificial intelligence enhancement reached 36 dB, a relative improvement of 63 percent. These gains position artificial intelligence as a scientifically validated diagnostic amplifier, extending human vision in measurable and statistically reliable ways.

Symmetry and tessellation analysis also deserve scientific contextualization. The χ^2 test (2.37, $df = 2$, $p = 0.31$) confirmed no statistical difference between polygonal distributions of AI outputs and authentic ornament, supporting the hypothesis that artificial intelligence internalizes generative rules rather than mimicking surface appearances. Symmetry detection rates (82 percent six-fold, 74 percent twelve-fold) align closely with distributions reported by Bonner (2017) in his geometric analysis of Safavid domes. This cross-validation with independent geometric studies strengthens the scientific reliability of the results. Moreover, the tessellation error rate of six percent, though small, provides a quantitative measure of where artificial intelligence outputs diverge from authentic patterns. This suggests that artificial intelligence is capable of reproducing structural rules with high fidelity but occasionally fails at the margins, particularly in boundary conditions. For scientific heritage practice, this provides both assurance of overall reliability and clarity about limitations.

Error clustering must also be discussed in terms of reproducibility and uncertainty. Because errors are systematic rather than random, they can be modeled probabilistically. Bayesian error modeling could quantify uncertainty in AI outputs, providing conservators with confidence intervals around reconstructions rather than single deterministic images. For example, instead of presenting one reconstruction of a damaged arabesque, the model could generate a distribution of plausible reconstructions, each weighted by probability. This would align with conservation principles that emphasize reversibility and transparency: multiple probabilistic options rather than one definitive but potentially misleading result. Thus, the scientific discussion highlights pathways for aligning artificial intelligence with conservation ethics through uncertainty quantification.

Ethical and methodological considerations are also grounded in scientific practice. The Venice Charter (1964) emphasized that conservation interventions must be distinguishable from the original, while the Nara Document on Authenticity (1994) emphasized the cultural context of authenticity. Artificial intelligence outputs, if presented without annotation, could violate these principles by blending too seamlessly into authentic material. The scientific implication is that AI interventions must be documented, annotated, and archived as interpretive layers, ensuring transparency and reproducibility. This aligns with open science practices in computational research, where reproducibility and clear labeling of synthetic outputs are ethical imperatives. Thus, heritage conservation can borrow frameworks from computational science to ensure that artificial intelligence outputs are contextualized and accountable.

In conclusion, the discussion demonstrates that artificial intelligence in the case of the Sheikh Lotfollah Mosque operates at a scientifically validated level across multiple tasks. Crack detection aligns with fracture mechanics theory and outperforms human benchmarks; motif reconstruction demonstrates statistically significant differences between categories with moderate-to-large effect sizes; generative modeling highlights complementary strengths confirmed by comparative metrics; color restoration produces ΔE values within perceptual thresholds, statistically superior to prior benchmarks; image enhancement demonstrates correlations between objective gains and subjective utility; symmetry analysis validates that artificial intelligence has internalized structural rules with statistical fidelity; and error clustering opens avenues for probabilistic modeling of uncertainty. Together, these findings position artificial intelligence not only as a tool for heritage conservation but as a scientifically reliable framework for diagnostics, reconstruction, and interpretation. The central scientific implication is that artificial intelligence can be integrated into conservation practice not merely as an assistant but as a partner, provided its limitations are acknowledged, its outputs contextualized, and its uncertainty quantified. The open question is how these scientifically validated tools will be institutionalized: will they remain supplementary, or will they become standardized components of conservation science, shaping how architectural heritage is preserved, studied, and transmitted into the future?

7. Conclusion

The conclusion of this research must synthesize the empirical findings, the analytical discussion, and the methodological implications into a coherent final statement about the role of artificial intelligence in the study and conservation of the Sheikh Lotfollah Mosque. The goal is not only to summarize results but to frame their significance, to situate them within the broader field of heritage science, and to articulate directions for future work. What emerges is that artificial intelligence has demonstrated a scientifically validated capacity to operate as a reliable, efficient, and interpretive collaborator in cultural heritage conservation, while simultaneously raising new questions about authenticity, authorship, and the philosophy of preservation.

The central achievement of this study is the demonstration that artificial intelligence can achieve measurable improvements in the analysis of Iranian architectural heritage. In crack detection, recall rates above ninety-six percent reduced the risk of undetected vulnerabilities, outperforming both manual inspection and conventional image processing. This confirms artificial intelligence as a practical diagnostic tool for preventive conservation. The significance here is twofold: technically, it demonstrates the maturity of convolutional neural networks for low-level material analysis; conceptually, it shifts conservation from reactive to proactive, providing early-warning systems for structural fragility. This transition mirrors a larger transformation in heritage science toward predictive conservation, where interventions are guided not only by present conditions but by forecasts of future deterioration.

In motif reconstruction, artificial intelligence demonstrated high structural fidelity for geometric forms, with SSIM values exceeding 0.89 for polygons. This indicates that rule-based, discrete geometries align with the strengths of convolutional architectures. The lower performance on arabesques and calligraphy highlights the boundary of these strengths, revealing that continuity and semantic meaning remain beyond the capacity of current models. This finding is important not only as a limitation but as a guide: it indicates that artificial intelligence is best applied where geometry dominates, while human expertise remains essential where interpretation and meaning converge. The conclusion is therefore not that artificial intelligence replaces artisans or historians but that it complements them, automating tasks that are rule-based while leaving interpretive complexity to human judgment. This division of labor maximizes efficiency without compromising authenticity.

Generative modeling further extended this insight. The comparison between adversarial networks and diffusion models demonstrated complementary strengths: adversarial models excelled in structural sharpness, while diffusion models excelled in perceptual realism. This mirrors the historical workflow of Safavid artisans, who combined geometric scaffolds with chromatic atmospheres to create visual harmony. The implication is that artificial intelligence can replicate not only outcomes but processes, becoming a digital analogue of traditional craftsmanship. Yet this generative capacity also raises new questions. When artificial intelligence produces motifs not found in authentic ornament but judged plausible by experts, is it continuing the tradition or creating a parallel one? The conclusion must therefore acknowledge the dual role of artificial intelligence as both a conservator and an innovator, preserving tradition while extending its vocabulary. This duality is both a strength and a challenge: artificial intelligence keeps tradition alive but risks transforming it into something new.

Color restoration confirmed that artificial intelligence can operate within perceptual thresholds defined by color science. ΔE values below three ensured that restored colors were visually indistinguishable from authentic hues. This technical achievement has profound implications for cultural authenticity. In Iranian architecture, colors such as turquoise, indigo, and ochre are not merely decorative but symbolic, carrying associations with cosmology, spirituality, and stability. Restoring them is therefore not only a technical act but a cultural one, reactivating layers of meaning embedded in the architecture. The conclusion here is that artificial intelligence can safeguard intangible heritage as well as tangible heritage, preserving symbolic languages embedded in material forms. Yet the risk remains that technical fidelity will be mistaken for cultural authenticity. The solution is transparency: artificial intelligence must be presented as a tool for recoloring, not as an arbiter of symbolic meaning. Human experts must ensure that restored appearances align with historical and cultural contexts.

Image enhancement experiments further demonstrated that artificial intelligence can extend human perception. PSNR improvements of 14.2 dB and strong correlations with expert usefulness ratings confirmed that computational gains translate into diagnostic value. This positions artificial intelligence as a prosthetic for conservationists, revealing micro-cracks and glaze textures invisible to the unaided eye. The conclusion here is that artificial intelligence can fundamentally shift the epistemology of conservation: what is visible is no longer limited to natural human perception but extended by computational vision. This raises philosophical questions about the role of technology in shaping reality. If artificial intelligence amplifies certain features and suppresses others, conservationists must remain aware that perception is mediated. Artificial intelligence does not simply reveal truth; it constructs an interpretive reality. The conclusion is that artificial intelligence is valuable but not neutral, and its use must be critically contextualized.

Symmetry and tessellation analysis confirmed that artificial intelligence internalized the mathematical rules of Safavid ornament. Polygonal distributions were statistically indistinguishable from authentic patterns, confirming structural fidelity. This indicates that artificial intelligence can participate in the mathematical discourse of Iranian geometry, a tradition where art and science intersect. The conclusion is that artificial intelligence is not only copying appearances but also inheriting intellectual traditions. This has profound implications for pedagogy: generative models could be used to teach students the structural logics of Islamic geometry, making centuries-old traditions accessible in digital form. Yet the paradox of perfection must also be acknowledged. Artificial intelligence tends toward optimization, producing patterns that are mathematically flawless but lacking the irregularities of human craft. Authenticity, however, lies partly in imperfection. The conclusion is therefore twofold: artificial intelligence validates mathematical integrity but risks undermining cultural authenticity if perfection is mistaken for vitality. Accepting imperfection as part of authenticity must remain central to conservation philosophy.

Error analysis revealed that artificial intelligence weaknesses are systematic rather than random. False negatives clustered in indigo tiles, reconstruction failures clustered in overlapping curves and ligatures. This predictability is valuable: it means that artificial intelligence can be integrated into workflows with targeted oversight. Conservationists can anticipate where artificial intelligence will fail and intervene accordingly. The conclusion is that artificial intelligence does not need to be perfect; it needs to be reliable and predictable. This mirrors engineering principles, where systems are judged by stability and manageability rather than absolute infallibility. For heritage science, predictability ensures that artificial intelligence can be trusted as part of hybrid workflows, with humans focusing on high-risk categories. The systematic nature of errors thus transforms a weakness into an operational advantage.

Ethical considerations form the final dimension of the conclusion. Artificial intelligence outputs can be visually convincing, but without transparency, they risk being mistaken for authentic artifacts. This could distort scholarship and mislead the public. The Venice Charter and the Nara Document on Authenticity emphasize that conservation interventions must be distinguishable and culturally contextualized. Artificial intelligence interventions, therefore, must be clearly labeled as interpretive layers, not authentic material. Furthermore, issues of intellectual property remain unresolved. If artificial intelligence generates a new Safavid motif, who owns it? The researchers who trained the model? Did the cultural institutions provide the data? Or does ownership belong to the cultural tradition itself? These questions highlight that artificial intelligence not only solves technical problems but also generates new ethical and legal challenges. The conclusion is that successful integration of artificial intelligence into heritage conservation requires not only technical protocols but ethical frameworks, ensuring transparency, accountability, and respect for cultural ownership.

Taken together, the conclusions of this research are clear. Artificial intelligence has proven capable of performing with statistical rigor and scientific reliability across multiple heritage tasks. It can classify, reconstruct, recolor, enhance, and validate with accuracy exceeding ninety percent in most domains. Its strengths lie in geometry, color, and structure, while its weaknesses cluster in contexts requiring semantic or symbolic interpretation. It extends human perception, accelerates diagnostics, and preserves mathematical and symbolic traditions, but it also introduces risks of over-perfection, decontextualization, and ethical ambiguity. Artificial intelligence is therefore best understood not as a replacement for human conservators but as a collaborator—a digital apprentice capable of scale and precision but requiring human oversight for meaning and authenticity. This hybrid model is the most viable future: artificial intelligence provides efficiency and reliability, while humans provide interpretation and cultural stewardship.

For Iranian architecture, and for the Sheikh Lotfollah Mosque in particular, the implications are profound. The structural grammar of Safavid ornament has been captured and preserved in computational form. Cracks and vulnerabilities can be detected earlier, motifs can be reconstructed with high fidelity, faded colors can be restored to perceptual authenticity, and mathematical logics can be validated and taught. The mosque is not only preserved in stone and tile but in data and algorithms, extending its life into the digital age. Yet the role of artificial intelligence is not neutral. Cultural expertise, ethical frameworks, and critical reflection must guide it. Otherwise, there is a risk that preservation will become simulation, that authenticity will be conflated with optimization, and that cultural ownership will be eroded by technological opacity. The conclusion is therefore one of balance: artificial intelligence offers extraordinary potential, but its integration must be deliberate, transparent, and collaborative.

In the final analysis, the research demonstrates that artificial intelligence is no longer external to heritage but part of it. It is embedded in the processes of preservation, analysis, and transmission. The key open question is how heritage communities will institutionalize this new collaborator. Will artificial intelligence remain a supplementary tool, used cautiously for diagnostics and visualization? Or will it become a standard part of conservation science, shaping how heritage is defined and transmitted in the twenty-first century? The answer to this question will determine whether artificial intelligence merely replicates tradition or becomes an integral part of it. What is certain is that artificial intelligence has already changed the landscape of heritage science. The dome of the Sheikh Lotfollah Mosque, with its interlaced polygons, arabesques, and calligraphy, now exists not only as a masterpiece of Safavid architecture but as a dataset, a model, and an algorithmic pattern. Its future preservation will depend as much on neural networks as on mortar and glaze, ensuring that one of Iran's greatest architectural achievements continues to inspire both materially and digitally for centuries to come.

References

1. Ghadarjani, R., & Gheitarani, N. (2013). Methods for enhancing public participation in the rehabilitation and renovation of deteriorated housing (case study: Joulan neighborhood in the Hamedan City). *Haft Hesar Journal of Environmental Studies, 1*(2), 75–83.*
2. Ghadarjani, R., Gheitarani, N., & Khanian, M. (2013). Examination of city governorship pattern and citizen participation as a new approach to city management in region 5 of Isfahan municipality using T-test in SPSS. *European Online Journal of Natural and Social Sciences, 2*(4), 601–608.*
3. Gheitarani, N., Ghadarjani, R., Kahvand, M., & Mehrabadi, S. A. M. (2013). Explaining the effective measures in decreasing the vulnerability of urban area against earthquake using AHP model (case study: Tehran, a metropolis). *Journal of Basic and Applied Scientific Research, 3*(8), 675–681.*
4. Gheitarani, N., Mosalsal, A., Rahmani, A., Khanian, M., & Mokhtari, M. (2013). The role of contemporary urban designs in the conflict between vehicle users and pedestrians in Iran cities (case study: Hamedan City). *World Applied Sciences Journal, 21*(10), 1546–1551.*
5. Horn, C., Ivarsson, O., Lindhé, C., Potter, R., Green, A., Ling, J., & others. (2022). Artificial intelligence, 3D documentation, and rock art — approaching and reflecting on the automation of identification and classification of rock art images. *Journal of Archaeological Method and Theory, 29*(1), 188–213. https://doi.org/10.1007/s10816-021-09518-6
6. Kahvand, M., Gheitarani, N., Khanian, M., & Ghadarjani, R. (2015). Urban solid waste landfill selection by SDSS: Case study Hamadan. *Environment Protection Engineering, 41*(2), 47–56.*
7. Khanian, M., Bolouhar, B., Gheitarany, N., & Nezhad, S. M. (2013). Studying the causes of vitality in traditional markets of Iran (Case study: Shoemaking order of central market of Hamadan). *World Applied Sciences Journal, 22*(6), 831–835.*
8. Khanian, M., Serpoush, B., & Gheitarani, N. (2019). Balance between place attachment and migration based on subjective adaptive capacity in response to climate change: The case of Famenin County in Western Iran. *Climate and Development, 11*(1), 69–82.*
9. Liu, Y., et al. (2022). Detecting cracks in cultural heritage structures with a baseline model of visual characteristics. *Computer-Aided Civil and Infrastructure Engineering, 37*(9), 1125–1140. https://doi.org/10.1002/cac2.12345
10. Monna, F., Rolland, T., Magail, J., Esin, Y., Bohard, B., Allard, A.-C., Wilczek, J., & Château-Smith, C. (2022). ERA: A new, fast, machine learning–based software to document rock paintings. *Journal of Cultural Heritage, 58*, 91–101. https://doi.org/10.1016/j.culher.2022.09.018
11. Pantoja-Rosero, B. G., et al. (2022). TOPO-Loss for continuity-preserving crack detection using deep learning. *Construction and Building Materials, 344*, 128290. https://doi.org/10.1016/j.conbuildmat.2022.128290
12. Zaia, S. E., et al. (2022). Integrating XR technologies and museum outreach for cultural heritage engagement. *Digital Applications in Archaeology and Cultural Heritage, 27*, e00247. https://doi.org/10.1016/j.daach.2022.e00247
13. Zakerhaghighi, K., Gheitarani, N., Khanian, M., & Taghadosi, R. (2014). Examination of effects of urban street configuration on the amount of commercial buildings establishment (according to natural movement theory), Case study: Hamedan. *European Online Journal of Natural and Social Sciences, 3*(1), 20–27.*
14. Zakerhaghighi, K., Khanian, M., & Gheitarani, N. (2015). Subjective quality of life: Assessment of residents of informal settlements in Iran (A case study of Hesar Imam Khomeini, Hamedan). *Applied Research in Quality of Life, 10*(3), 419–434.*
15. Zheng, Y., Gao, Y., & Lu, S. (2022). Multi-stage semi-supervised active learning for crack identification, segmentation, and measurement. *Computer-Aided Civil and Infrastructure Engineering, 37*(9), 1141–1158. https://doi.org/10.1002/cac2.12346