

Article

A Novel Reversible Data Hiding Method with Contrast Enhancement Based on Order and Brightness Preservation

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Abstract

With the widespread adoption of the Internet and smart devices, protecting digital information during transmission has become increasingly important. Reversible Data Hiding (RDH) enables secret data to be embedded into digital images while allowing both the hidden data and the original image to be recovered losslessly. To improve image quality, Contrast Enhancement (CE) techniques have been integrated into RDH methods to enhance image details and features. However, existing CE-RDH methods often suffer from excessive enhancement and visual distortion at high embedding rates, resulting in unnatural brightness variation and degradation of visual quality. Therefore, this study proposes a novel reversible data hiding method with contrast enhancement based on order and brightness preservation. An adaptive histogram bin merging strategy and histogram stretching technique are employed during preprocessing to improve embedding capacity and contrast enhancement performance while preserving pixel order and reducing intensity mismatch artifacts. In the data embedding stage, a brightness-preserving embedding mechanism is adopted to adaptively adjust the embedding direction according to image brightness, preventing over-enhancement and maintaining visual consistency. Experimental results on the USC-SIPI and Kodak datasets demonstrate that the proposed method increases embedding capacity by 5–40% while maintaining Relative Mean Brightness Error (RMBE) above 0.99, Peak Signal-to-Noise Ratio (PSNR) above 24.2 dB, and Structural Similarity Index Measure (SSIM) above 0.882, outperforming existing CE-RDH methods in brightness preservation, visual quality, and contrast enhancement performance.

Keywords: reversible data hiding; contrast enhancement; brightness preservation

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1. Introduction

In recent years, with the high prevalence of the Internet and smart devices, the applications of information have become extremely widespread, making people's daily interactions increasingly convenient. However, this has also brought a certain level of risk: hackers may steal information during transmission, threatening the privacy and security of user data. Data Hiding (DH) [1,2] is a method of embedding secret messages into media for transmission. Since the media itself does not undergo significant changes, it is difficult for others to detect. Digital images are commonly used as carriers because slight modifications are difficult for the human eye to detect. Because the difference between the stego image and the original image is extremely small, it is very difficult for hackers to identify whether

the transmitted image is a stego image, making the hidden secret message even harder to decode. In addition, data hiding can also be applied to image intellectual property protection. To better confirm the ownership of image intellectual property, users can embed identity verification data or signatures into images using data hiding techniques as a basis for identifying image ownership.

To better preserve the transmitted media and messages, researchers proposed Reversible Data Hiding (RDH) [3,4], also known as lossless data hiding. This ensures that secret messages can be extracted losslessly from stego images and the images can be converted back to the original. Most RDH methods are proposed for digital images; however, the data embedding process may introduce unnecessary distortion, making it difficult to improve visual quality. Furthermore, constrained by the imaging illumination environment, some images suffer from poor brightness performance, which in turn affects visual quality. Therefore, to better present the details and features within images, RDH methods have been combined with Contrast Enhancement (CE) [5] image processing techniques, improving image quality by enhancing the brightness differences between image pixels. These methods are generally referred to as CE-RDH methods.

To further improve CE-RDH performance, researchers have proposed several enhanced preprocessing and embedding strategies in recent years. In 2015, Wu et al. were the first to propose a reversible data hiding method based on contrast enhancement (RDHCE) [6], which was the first CE-RDH method. By shifting the histogram to embed data, it achieves the effect of Histogram Equalization (HE) [7] during the process, thereby improving the visual quality of the image. To avoid pixel overflow or underflow during embedding, pixels are modified in the pre-processing step. However, at high embedding rates, the pre-processing method of RDHCE is likely to introduce Intensity-Mismatched Artifacts, degrading image quality. To avoid such artificial distortions, researchers improved the pre-processing by shifting the image histogram while preserving the pixel order, restricting histogram bins to merge only with adjacent bins. This approach is referred to as order-preserving pre-processing [8–10]. By preserving the ordering of pixel values, intensity mismatch artifacts are mitigated. Even with improvements to pre-processing, another source of visual distortion remains: at high embedding rates, image brightness may become excessively enhanced as contrast increases, making the image look unnatural visually. Therefore, researchers began incorporating Brightness Preservation (BP) into their methods to avoid over-enhancement and achieve better visual results [11,12]. To further enhance image details, some CE-RDH methods incorporate background segmentation [13–15] in pre-processing to enhance specific image regions and highlight their details and features. In addition to one-dimensional HE, methods using modified two-dimensional (2D) histograms for CE-RDH have also been proposed [16,17], achieving better image quality and CE visual performance.

Although existing CE-RDH methods have improved embedding capacity and contrast enhancement performance, several limitations still remain. First, some preprocessing methods may still introduce visual distortion due to inappropriate histogram merging. Second, excessive embedding operations may lead to over-enhancement and brightness inconsistency at high embedding rates. Third, improving embedding capacity often increases image distortion, making it difficult to balance embedding performance and visual quality simultaneously.

Existing CE-RDH methods have primarily focused on improving individual aspects of the embedding process rather than providing a comprehensive solution. For example, the RDHCE method [6] achieves reversible data hiding with contrast enhancement through histogram equalization but may introduce intensity mismatch artifacts during preprocessing. The OPHBE method [9] alleviates this problem by preserving pixel order during histogram

merging; however, its preprocessing strategy still relies on a predetermined number of embedding rounds and does not explicitly optimize embedding capacity. Shi et al. [12] further improve visual quality by introducing a brightness-preserving embedding strategy, but the preprocessing stage remains unchanged and therefore cannot fully exploit the histogram distribution for capacity enhancement. Consequently, existing approaches generally improve either preprocessing, brightness preservation, or embedding strategy individually, while the integration of these complementary techniques into a unified CE-RDH framework remains largely unexplored.

To overcome the limitations of existing CE-RDH methods, this study proposes a novel reversible data hiding method with contrast enhancement based on order and brightness preservation. Unlike previous methods that mainly improve individual components of the CE-RDH framework, such as order-preserving preprocessing [9,10], brightness-preserving embedding [12], or histogram-based contrast enhancement [6,13,16], the proposed method integrates adaptive histogram bin merging, histogram stretching, and brightness-preserving single-peak embedding into a unified framework. The adaptive histogram bin-merging strategy selectively merges dominant histogram bins to increase embedding capacity while preserving pixel order and reducing intensity mismatch artifacts. Histogram stretching further improves contrast distribution before data embedding, whereas the proposed brightness-preserving embedding strategy adaptively determines the embedding direction according to image brightness to prevent over-enhancement and maintain visual consistency. Experimental comparisons with representative CE-RDH methods [6,9,10,13,16] on the USC-SIPI [18] and Kodak [19] datasets demonstrate that the proposed framework achieves superior embedding capacity, brightness preservation, and overall image quality, as evaluated using PSNR, SSIM [20], BRISQUE [21], RCE, REE, and RMBE [22].

The main contributions of this study are summarized as follows:

- An adaptive histogram bin-merging strategy is proposed to selectively merge dominant histogram bins according to histogram statistics rather than relying on a predetermined number of embedding rounds. This strategy increases embedding capacity while preserving pixel order and reducing intensity mismatch artifacts.
- A unified preprocessing framework integrating adaptive histogram bin merging and histogram stretching is introduced to simultaneously improve embedding capacity and contrast enhancement before data embedding, providing a more effective preprocessing strategy than existing CE-RDH methods.
- A brightness-preserving single-peak embedding strategy is developed to adaptively determine the embedding direction according to image brightness, thereby reducing over-enhancement while maintaining visual consistency and high image quality.
- Comprehensive experiments on the USC-SIPI and Kodak datasets demonstrate that the proposed framework consistently achieves higher embedding capacity, better brightness preservation, and competitive image quality compared with representative CE-RDH methods.

The remainder of this paper is organized as follows. Section 2 discusses in detail the different categories of CE-RDH methods and their implementations, reviewing the evolution of CE-RDH methods. Section 3 presents the detailed workflow of the proposed method, including pre-processing, data embedding, and recovery. Section 4 evaluates the performance of the proposed method using two different image datasets. Finally, Section 5 summarizes the entire paper and draws conclusions.

2. Literature Review

First, Section 2.1 introduces the contrast enhancement approach in RDH methods. Then, Section 2.2 introduces CE-RDH methods that use order-preserving pre-processing.

Finally, Section 2.3 introduces CE-RDH methods that use BP. Since many variable symbols are used in the subsequent method descriptions, Table 1 provides an explanation.

Table 1. Symbol Table.

Symbol	Description
I	The original image.
I'	The modified image, also known as the stego image.
M	The height of the original image.
N	The width of the original image.
B	The brightness value of the original image I .
B'	The brightness value of the stego image I' .
p_i	The original image pixel value, such that $p_i \in \{0, 1, \dots, 254, 255\}$.
p'_i	The pre-processed image pixel value, such that $p'_i \in \{0, 1, \dots, 254, 255\}$.
q_i	The stego image pixel value, such that $q_i \in \{0, 1, \dots, 254, 255\}$.
$H(p_i)$	The height of p_i in H , also the number of occurrences of p_i in the image, referred to as the histogram bin.
PL, PR	The pixel value with the highest frequency in the image, referred to as the Peak Points at left or right side.
Z	The pixel value with the lowest frequency in the image.
b_k	The k -th message bit to be embedded, composed of binary 0 and 1.
S	The number of embedding rounds using a peak pair.
s	The number of embedding rounds using a single peak. ($S = 2s$).
I_{max}	The maximum value of image pixels.
I_{min}	The minimum value of image pixels.
L_{max}	The maximum boundary of the image target range; for grayscale images, this value is typically 255.
L_{min}	The minimum boundary of the image target range; for grayscale images, this value is typically 0.

2.1. RDH with Contrast Enhancement

CE-RDH is a method that implements data hiding and contrast enhancement in digital images. Its workflow encompasses the data embedding stage from the original image to the contrast-enhanced image, as well as the recovery process of extracting hidden data from the contrast-enhanced image, as shown in Figure 1. In the data hiding stage, the original image is first pre-processed, which includes image transformation, background segmentation, histogram stretching, or prevention of pixel overflow and underflow. The embedded secret messages can be various types of data, embedded in binary format. A contrast-enhanced image, also known as the stego image, is generated by modifying the histogram. In the information extraction and recovery stage, by reversing the histogram modification process, the secret information embedded in the stego image can be extracted losslessly. Finally, through a post-processing step, the stego image can be losslessly restored, thus implementing the reversibility of the data hiding method.

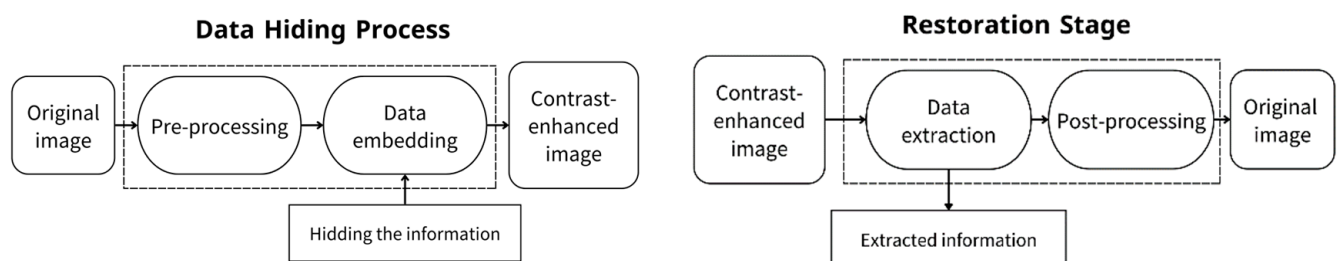


Figure 1. Flowchart of the data hiding process.

To simultaneously perform data hiding and contrast enhancement, CE-RDH methods embed data and achieve contrast enhancement by modifying the image histogram. Most CE-RDH methods use histogram equalization to embed data and achieve image contrast enhancement. Histogram Equalization (HE) is an image processing technique that

redistributes the gray-scale values of an image to make the histogram distribution more uniform. Taking the RDHCE method proposed by Wu et al. [6] as an example, directly shifting the boundary bins (0 and 255) during bin shifting would cause pixel overflow or underflow. Compared with RDHCE, subsequent order-preserving methods achieved lower visual distortion by restricting histogram merging to adjacent bins. A parameter S is first set, representing the total number of embedding rounds for an image. To avoid pixel overflow, bins $[0, S - 1]$ and $[256 - S, 255]$ are merged towards the center of the histogram with bins $[S, S - 1]$ and $[256 - 2S, 255 - S]$ according to parameter S . Taking $S = 1$ as an example, the boundary bins 0 and 255 are merged with 1 and 254, respectively, thus preventing overflow, as shown in Figure 2. In addition, a binary location map (LM) of the same size as the original image is generated during the process, recording non-overflow or overflow bin positions with 0 or 1. The location map, secret messages, and other auxiliary information are then embedded into the stego image during data embedding. Only the boundary histogram bins are shown for clarity because the remaining histogram bins are unchanged during preprocessing.

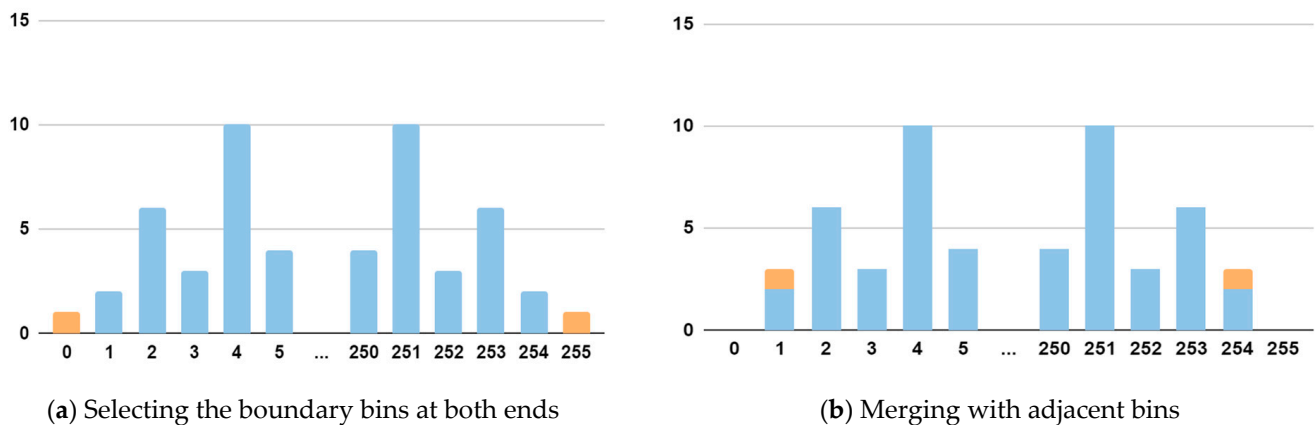


Figure 2. Pre-processing method of RDHCE ($S = 1$). Blue bars represent unchanged histogram bins, and orange bars represent the boundary histogram bins selected for preprocessing.

In the data embedding stage, the two highest and second-highest peak bins (P_L, P_R) are first found from the histogram, assuming $P_L < P_R$. Then, the bins on both sides of the peaks ($p_i < P_L$ or $p_i = P_R$) are each shifted outward (towards the histogram boundary) by one position. This shifting provides sufficient expansion space for the two peak bins (P_L, P_R), namely $P_L - 1$ and $P_R + 1$ respectively. The selected peak bins (P_L, P_R) are then expanded using Equation (1), where P_L is equally split into P_L and $P_L - 1$, and P_R is equally split into P_R and $P_R + 1$. The bins between the two peaks remain unchanged ($P_L < p_i = P_R$), as shown in Figure 3. During data embedding, the allocation of peak bins differs based on the embedded secret message bit b_k (0 or 1). This allows the peaks to be equally distributed into two adjacent bins of similar heights, achieving both data embedding and contrast enhancement. Only the histogram bins involved in the embedding process are for clarity; the omitted histogram bins remain unchanged during this embedding operation.

$$q_i = \begin{cases} p_i - 1, & \text{if } p_i < P_L \\ p_i - b_k, & \text{if } p_i = P_L \\ p_i, & \text{if } P_L < p_i < P_R \\ p_i + b_k, & \text{if } p_i = P_R \\ p_i + 1, & \text{if } p_i > P_R \end{cases} \quad (1)$$

Finally, by repeatedly expanding the two highest peaks in the histogram to reduce their heights, the pixel distribution can be effectively adjusted, gradually equalizing the histogram as the number of embedding rounds increases. However, since this approach relies on the amount of embedded data for contrast enhancement, if the amount of embedded data is small, there will be no significant contrast enhancement. Conversely, if the amount of embedded data is too large, the image may become overexposed or excessively enhanced, losing the original details of the image.

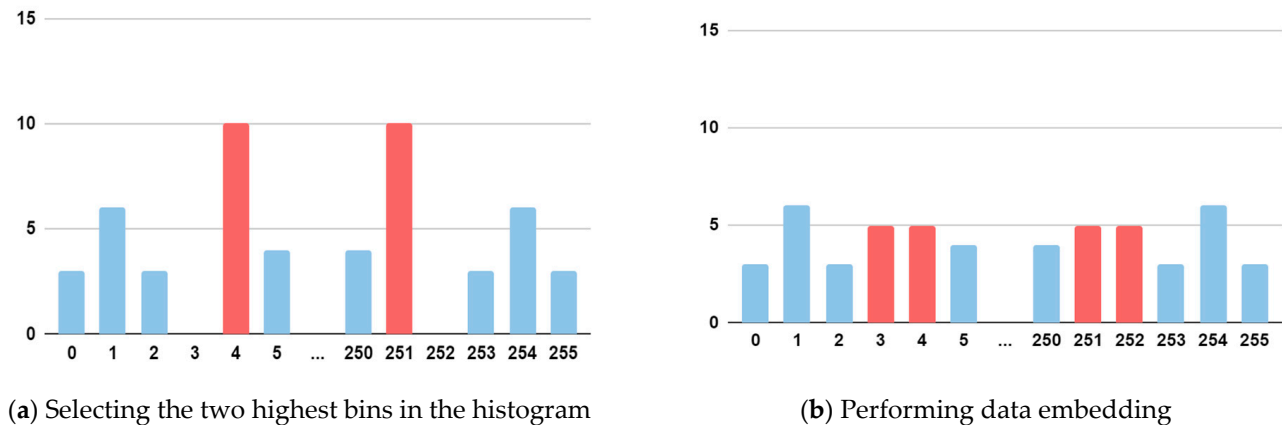


Figure 3. Histogram equalization embedding method ($S = 1$). Blue bars represent unchanged histogram bins, whereas red bars represent the peak histogram bins selected for data embedding.

To more effectively enhance image contrast, some CE-RDH methods [12,14,15] perform histogram stretching during the image pre-processing stage. Histogram Stretching (HS) is an image processing technique that expands the gray-scale range of an image to enhance contrast. Using Equation (2), the maximum (I_{max}) and minimum (I_{min}) pixel values of the image are remapped to the maximum (L_{max}) and minimum (L_{min}) gray-scale values of the displayable range, typically 255 and 0, thereby widening the histogram distribution range and increasing the difference between pixel values, as shown in Figure 4. Since HS uses linear transformation to modify the histogram, it does not change the relative order between pixels, does not cause excessive contrast enhancement, and preserves the original distribution of the image. HS is typically performed at the pre-processing stage and is more suitable for images with distinct features but poor contrast, effectively improving the local details of the image.

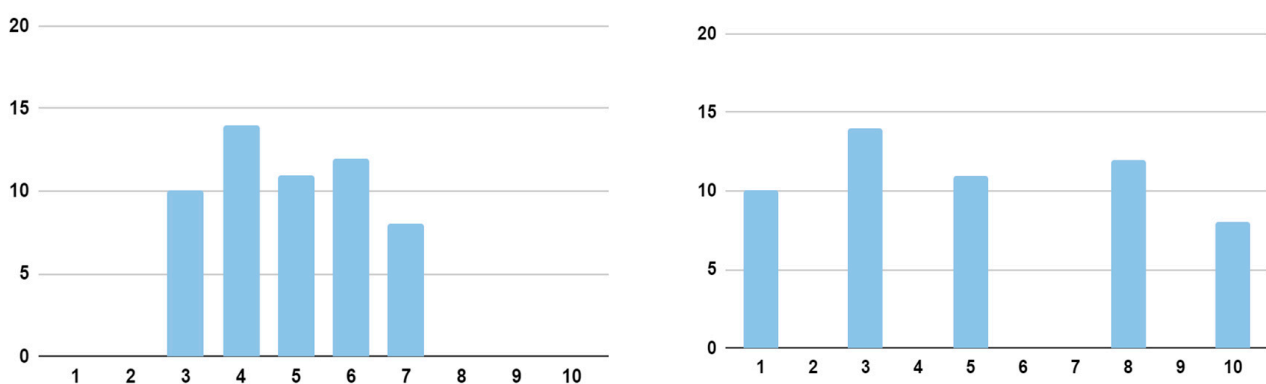


Figure 4. Histogram stretching.

Recent studies have further advanced contrast-enhancement-based reversible data hiding through adaptive histogram manipulation and automatic enhancement strategies. Zhang et al. [23] proposed an adaptive multi-histogram reversible data hiding method

that improves contrast enhancement by dynamically partitioning histogram regions, while Gao and Amoah [24] introduced an automatic contrast enhancement framework based on bi-histogram shifting to achieve improved embedding performance with enhanced visual quality. Lyu et al. [25] further enhanced automatic contrast enhancement using histogram expansion to improve embedding efficiency and image perception. These studies demonstrate the continued development of histogram-based CE-RDH methods while highlighting the importance of adaptive histogram processing.

$$p'_i = \text{round}[(L_{\max} - L_{\min}) \times \frac{p_i - I_{\max}}{I_{\max} - I_{\min}} + I_{\min}] \quad (2)$$

2.2. RDH with Order Preservation

The RDHCE method proposed by Wu et al. [6] requires pre-processing to avoid pixel overflow or underflow during the data hiding process, which is necessary and unavoidable. However, its pre-processing approach may produce Intensity-Mismatched Artifacts due to intensity mismatches between pixels, causing visible visual distortion during the contrast enhancement process and making important features and details in the image blurry. Intensity mismatch artifacts refer to the situation in pre-processing where bins with different pixel values are merged, causing originally adjacent bins to become far apart. When S is small or only a few pixels are affected, the artifacts in the image are subtle and nearly invisible, but when S is large or more pixels are affected, the artifacts become very prominent and obvious. Taking $S = 2$ as an example, boundary pixel values $[0, 1]$ and $[254, 255]$ are merged with $[2, 3]$ and $[252, 253]$, respectively, disrupting the original pixel order.

To address the artificial distortions caused by the aforementioned pre-processing method, researchers proposed several methods that can adaptively select the optimal merging strategy based on image characteristics [8,9] to achieve high embedding capacity and low distortion. Since the main cause of visual distortion is the disorder resulting from modifications to the pixel ordering, effectively limiting pixel order changes during pre-processing can reduce visual distortion.

Wu et al. improved the pre-processing method and proposed an order-preserving pixel-based pre-processing approach [9], namely order-preserving histogram bin expansion (OPHBE). Similar to the pre-processing of RDHCE, S boundary bins are selected from both sides according to the number of embedding rounds S and merged with adjacent bins, thereby obtaining the space needed for data embedding. The only difference is that the OPHBE method selects bins at intervals for merging, which effectively limits the histogram to only merge adjacent bins during the merging process. In this way, pixel order can be maintained while creating space, thus avoiding the artificial distortions caused by intensity mismatches in the RDHCE pre-processing method. Although order-preserving preprocessing effectively reduces intensity mismatch artifacts, excessive embedding operations may still cause over-enhancement and brightness inconsistency in enhanced images. Taking $S = 2$ as an example, RDHCE directly merges boundary bins $[0, 1]$ and $[254, 255]$ with $[2, 3]$ and $[252, 253]$, respectively, changing the order between pixels, as shown in Figure 5. OPHBE [9], on the other hand, uses interval bin selection for merging: merging 0 with 1, 2 with 3, 253 with 252, and 255 with 254, effectively preserving pixel order, as shown in Figure 6.

2.3. RDH with Brightness Preservation

Even with improvements to the pre-processing process, another cause of visual distortion remains: during the data hiding process, embedding too much data may cause the image to be over-enhanced, leading to overexposure and actually blurring the de-

tails and features that should have become clearer. For this type of distortion, brightness preservation can be used to limit the contrast and brightness of the image, allowing it to adaptively adjust the data embedding approach based on the current brightness state of the image during embedding, ensuring that the image does not become over-enhanced, thereby mitigating visual distortion. The method proposed by Shi et al. improved the embedding direction of secret messages [12], comparing the current histogram brightness with the original image brightness to determine the embedding direction. More recent studies have extended brightness-preserving CE-RDH techniques to specific application domains. Gao et al. [26] proposed a multi-group stretching strategy for reversible data hiding in medical images, improving both contrast enhancement and region-of-interest preservation. Gandhi and Kumar [27] further developed a high-capacity CE-RDH framework that combines brightness preservation with enhanced embedding performance for medical images. These studies demonstrate that brightness preservation remains an active research direction, particularly for applications requiring high visual fidelity, such as medical image processing.

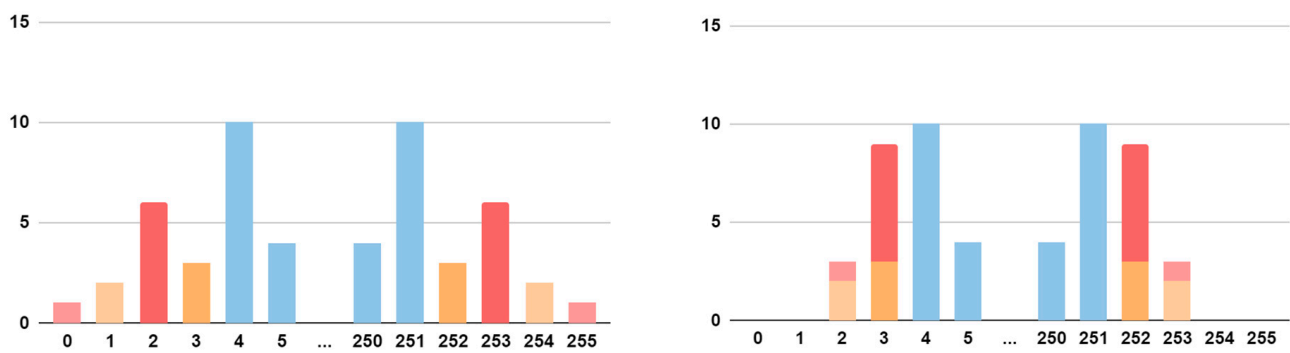


Figure 5. Pre-processing method of RDHCE ($S = 2$). Blue bars represent unchanged histogram bins, red and orange bars represent the histogram bins involved in the preprocessing operation.

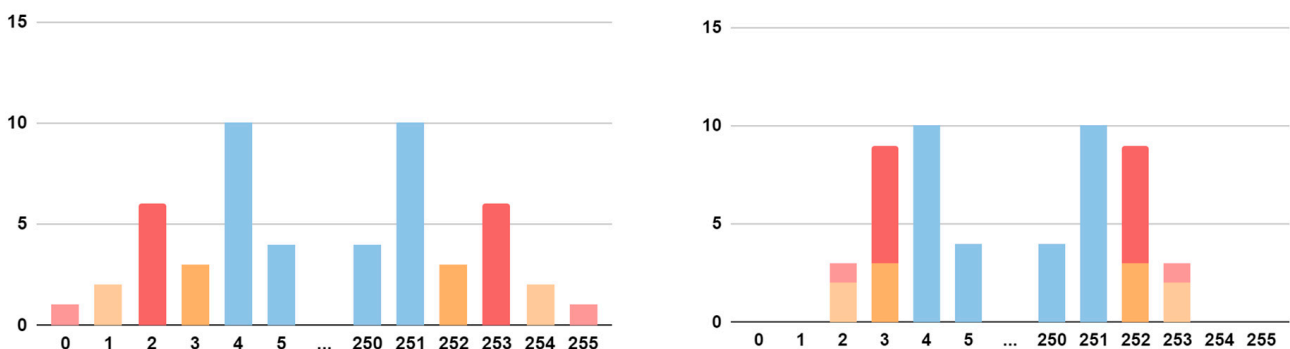


Figure 6. Order-preserving pre-processing method of OPHBE ($S = 2$). Blue bars represent unchanged histogram bins, red and orange bars represent the histogram bins involved in the preprocessing operation.

$$B = \frac{1}{M \times N} \sum_{i=1}^I p_i \quad (3)$$

$$d = \begin{cases} 0, & \text{if } B' > B \\ 1, & \text{if } B' < B \end{cases} \quad (4)$$

If the brightness value B' of the expanded histogram is greater than the brightness value B of the original image, data embedding is performed leftward ($d = 0$), reducing image brightness by equally distributing the peak into PH and $PH-1$. Conversely, if B' is less than B , data embedding is performed rightward ($d = 1$), distributing the peak into PH and $PH + 1$ to increase image brightness, as shown in Figure 7. As the number of embedding

rounds increases to raise or lower brightness, the stego image brightness is adjusted to match the original image. Brightness-preserving methods improve visual consistency and reduce over-enhancement effects; however, balancing embedding capacity, contrast enhancement, and image quality remains a challenging issue.

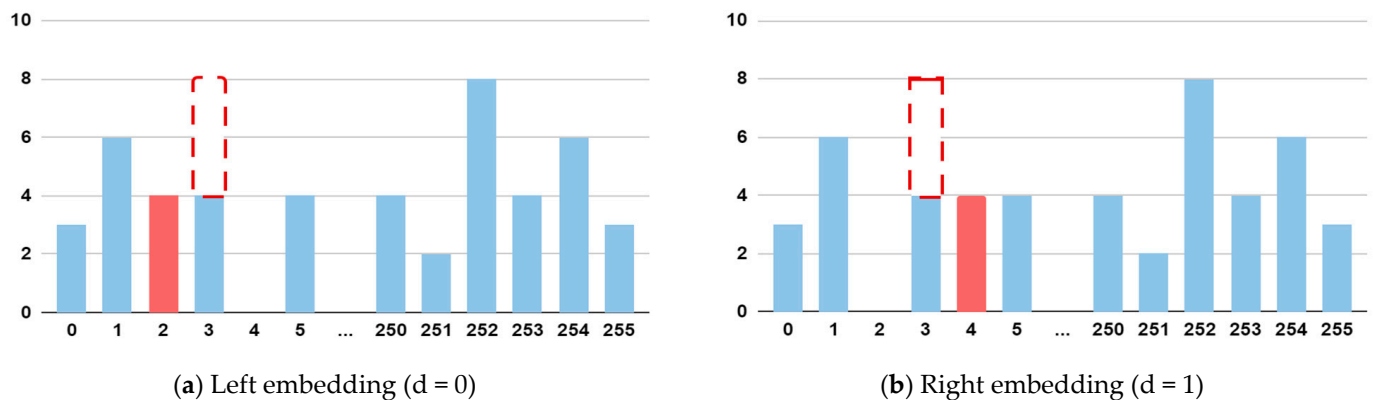


Figure 7. Brightness-preserving embedding method. Blue bars represent unchanged histogram bins, the red bar represents the selected peak histogram bin, and the red dashed box indicates the expanded histogram bin.

Based on the above review, existing CE-RDH methods have made significant progress in improving reversible data hiding and contrast enhancement. Early approaches primarily focused on histogram shifting and histogram equalization to simultaneously achieve data embedding and contrast enhancement. Subsequent studies introduced order-preserving preprocessing to reduce intensity mismatch artifacts, while brightness-preserving embedding strategies were developed to alleviate over-enhancement and improve visual consistency. More recently, histogram stretching and adaptive preprocessing techniques have been incorporated to further improve image contrast and embedding performance.

Despite these advances, several research challenges remain. Most existing methods improve only individual components of the CE-RDH framework, such as preprocessing, embedding strategy, or brightness preservation, without jointly optimizing these processes. Consequently, limitations remain in balancing embedding capacity, brightness consistency, and image quality, particularly under high embedding rates. Furthermore, preprocessing strategies are generally designed according to predetermined embedding rounds rather than adaptively exploiting histogram characteristics to maximize embedding efficiency.

Motivated by these observations, the proposed method integrates adaptive histogram bin merging, histogram stretching, and brightness-preserving single-peak embedding into a unified CE-RDH framework. By jointly optimizing preprocessing and embedding, the proposed framework increases embedding capacity while preserving pixel order, reducing brightness distortion, and maintaining superior visual quality.

To provide a clearer comparison of representative CE-RDH approaches, Table 2 summarizes their major characteristics, including preprocessing strategy, order preservation, brightness preservation, histogram stretching, embedding strategy, and their primary advantages and limitations. This comparison highlights the research gap addressed by the proposed framework.

Table 2. Comparison of representative CE-RDH approaches.

Study	Preprocessing Strategy	Order Preservation	Brightness Preservation	Histogram Stretching	Embedding Strategy	Key Limitations
Wu et al. [6]	Boundary bins $[0, S - 1]$ and $[256 - S, 255]$ merged toward center	✗	✗	✗	Dual peak HE embedding; iterative histogram shifting;	Introducing Intensity Mismatch Artifacts at high S, degrading image quality
Kim et al. [8]	Adaptively selects optimal merging strategy based on image characteristics	✓	✗	✗	Histogram-based automatic contrast enhancement	No brightness preservation; does not explicitly optimise embedding capacity
Wu et al. [9]	Interval bin selection: merges only adjacent bins at intervals, preserving pixel order	✓	✗	✗	Dual-peak expansion; predetermined S embedding rounds	Preprocessing relies on predetermined S rounds; does not explicitly optimise embedding capacity;
Wu et al. [13]	Background segmentation to extract specific image regions for selective enhancement	✗	✗	✗	Histogram-based CE-RDH targeting region of interest (ROI)	No order preservation; introduces observable artificial distortions
Shi et al. [12]	Histogram stretching applied during pre-processing stage	✗	✓	✓	Single-peak embedding; brightness-guided direction d determined by comparing B' with B	Preprocessing stage remains unchanged and cannot fully exploit histogram distribution for capacity enhancement
Lee et al. [10]	Order-preserving preprocessing adapted for colour medical images	✓	✗	✗	Dual-peak CE-RDH embedding applied to colour medical images	No brightness preservation; embedding capacity not explicitly optimised
Wu et al. [16]	Two-dimensional histogram construction from pixel pairs	—	✗	✗	2D histogram modification; joint peak-pair selection for CE and data embedding	No brightness preservation; RMBE declines with increasing S
Proposed Method	Adaptive dominant-bin merging + histogram stretching	✓	✓	✓	Single-peak embedding; brightness-guided adaptive direction d;	Single-peak embedding requires $\sim 2\times$ to achieve equivalent shifting as dual-peak methods

Note: ✓ indicates Yes, ✗ indicates No, and — indicates Not applicable.

3. Proposed Method

The proposed CE-RDH framework consists of three major stages: preprocessing, data embedding, and recovery. First, histogram bins with heights exceeding the average threshold are merged with adjacent bins to increase embedding capacity while preserving pixel order. Histogram stretching is then applied to improve contrast distribution. Next, a brightness-preserving embedding strategy adaptively selects the embedding direction according to image brightness to prevent over-enhancement. Finally, the recovery process extracts the embedded information and restores the original image losslessly.

3.1. Proposed Pre-Processing Method

Since histogram equalization and embedding of an image are completed through multiple repetitions, each repetition moves pixels from the highest peak to the lowest bin, causing the peak bins to be distributed across multiple bins while the lower bins are merged into other bins. Therefore, to effectively increase the embedding capacity per round, the selected peak should be as high as possible, and the number of peaks after expansion should approach the image average to achieve the results of histogram equalization.

$$T = \frac{M \times N}{\text{Number of image bins}} \quad (5)$$

The threshold T represents the average histogram height and is used to identify dominant histogram bins. Bins with heights greater than T are considered suitable candidates for merging because they contribute more significantly to embedding capacity.

$$lm_p(p_i) = \begin{cases} 1, & \text{if } H(p_i) > T \\ 0, & \text{else} \end{cases} \quad (6)$$

The location map records whether a histogram bin has been merged during preprocessing. This information is required to ensure complete reversibility during image recovery.

This study merges bins with histogram heights greater than the average with adjacent bins, increasing the height of each bin in the image histogram. The average histogram height is adopted as an adaptive merging threshold because it reflects the overall histogram distribution without requiring manually selected parameters. Histogram bins with frequencies above average generally contain sufficient pixels for reliable merging, allowing embedding capacity to be increased while avoiding excessive histogram modifications and preserving the global histogram characteristics. In this way, not only can the empty bins needed for data embedding be obtained in advance, but the embedding capacity per round can also be increased. A location map is used during the process to ensure subsequent lossless recovery. Since adjacent bins are merged, intensity mismatch distortion is also avoided. Given the same amount of embedded information, as the single-round embedding capacity increases, the number of bins that need to be shifted decreases. Therefore, if histogram equalization is only performed alongside data embedding, the degree of contrast enhancement will be limited. To better enhance image contrast, the merged histogram is further adjusted through histogram stretching to redistribute the pixel distribution, thus improving the image quality after pre-processing. Unlike OPHBE, which determines embedding space according to the number of embedding rounds, the proposed method adaptively merges dominant histogram bins to increase embedding capacity while reducing unnecessary histogram shifts.

The proposed preprocessing Algorithm 1 stage aims to improve embedding capacity while preserving pixel order and reducing intensity mismatch distortion.

Algorithm 1: Proposed Preprocessing Method

Input: Original image I

Output: Preprocessed image p'_i

Step 1: Calculate the image histogram H .

Step 2: Compute the histogram average threshold T using Equation (5).

Step 3: Record the maximum and minimum pixel values (I_{max} , I_{min}).

Step 4: For each side of the histogram:

(a) Mark all non-empty bins.

(b) If the histogram bin height exceeds threshold T , merge adjacent bins.

(c) Record the merging information using Equation (6).

Step 5: Apply histogram stretching using Equation (2).

3.2. Proposed Data Embedding Method

In the data embedding stage, to more effectively control image brightness variation, each embedding round selects only the current highest peak (P_s) for expansion, and adaptively selects the embedding direction based on the current brightness value (B') of the

image, that is, by comparing the brightness of the pre-processed image with that of the original image. Using a single peak instead of a peak pair reduces histogram modification during each embedding round, helping preserve image brightness and minimize visual distortion. The embedding direction (d) is then changed to increase or decrease the brightness of the pre-processed image, thereby achieving brightness preservation. This adaptive strategy compensates for brightness variations introduced during histogram modification by dynamically selecting the embedding direction according to the current image brightness. Consequently, cumulative brightness shifts over multiple embedding rounds are effectively reduced, leading to improved brightness consistency while maintaining reversible embedding performance.

$$lme(p'_i) = \begin{cases} 1, & \text{if } p'_i = Z_S \\ 0, & \text{else} \end{cases} \quad (7)$$

$$q_i = \begin{cases} p'_i + d, & \text{if } p'_i = Z_S \\ p'_i + d \times b_k, & \text{if } p'_i = P_S \\ p'_i + d, & \text{if } I_L < p'_i < I_R \\ p'_i, & \text{else} \end{cases} \quad (8)$$

where P_S denotes the selected peak bin, Z_S represents the lowest bin selected for shifting, d indicates the embedding direction, and b_k denotes the embedded secret bit.

Since the pre-processing method proposed in this study does not obtain sufficient embedding space based on the number of embedding rounds like OPHBE [9], it is necessary to verify whether there is sufficient space for data embedding before embedding, to avoid pixel overflow or underflow during the data embedding process. First, the highest peak (P_S) is selected from the histogram as the reference point to search in the embedding direction (d). If there is no empty bin available for embedding, the lowest bin (Z_S) within the range is selected for shifting. To better preserve image brightness, the shifting direction of Z_S is the same as the embedding direction of the peak (P_S), and it is merged with the adjacent bin in the embedding direction. When pixels are merged, a location map (lme) of the same size as the original image is also generated to record the modified pixel data, as shown in Equation (7).

To losslessly extract the secret message and recover the stego image to the original image, the final embedding peak P_S and embedding direction d , totaling 9 bits of data, are stored in the Least Significant Bits ($LSBs$) of the last 9 pixels. Nine bits are sufficient to record the final embedding position and embedding direction while introducing negligible distortion to the stego image. Therefore, these 9 $LSBs$ are excluded during the last embedding round. Additionally, to better distinguish whether Z_S has been shifted, an extra variable (Z_m) is added. When Z_S is shifted in that round, $Z_m = 1$; otherwise, $Z_m = 0$. Since the first embedding round does not require recording the location and direction of the previous embedding, the original image pixel range I_{max} and I_{min} can be embedded together with the secret message. The detailed embedding information is as follows:

first round secret message: [$I_{min}, I_{max}, Z_S, Z_m, b_k$]

middle rounds secret message: [P_S, d, Z_S, Z_m, b_k]

last round secret message: [$P_S, d, Z_S, Z_m, b_k, 9LSBs$]

additional information in last 9 $LSBs$: [P_S, d]

Through adaptive peak expansion and brightness-guided embedding, the proposed method simultaneously achieves data hiding, contrast enhancement, and brightness preservation.

The proposed embedding process adaptively determines the embedding direction according to image brightness to preserve visual consistency during contrast enhancement as presented in Algorithm 2.

Algorithm 2: Proposed image contrast enhancement process

Input: An image to be enhanced, denoted by I

Output: Contrast-enhanced image, denoted by I'

Parameter: Number of the histogram bin to be expanded (i.e., s)

Carry out the pre-processing on I and generate the bookkeeping data
 Find out the histogram bins of the pre-processed image;
 Calculate the brightness of the original image with Equation (3), parameter B ;
 Calculate the brightness of the pre-processed image with Equation (3), parameter B' ;
 Apply Equation (4) to determine the embedding direction d ;
 Apply Equation (8) to every pixel by scanning the image in the raster order to embed the bookkeeping data and its length, as well as other data;
 Count number of the empty bins;
 Find out the highest bins in the modified histogram do
 While the number of the empty bins is less than 0 then
 Search from the highest bin to the lowest bin in the embedding direction;
 Merge the lowest bin with adjacent bins in the embedding direction;
 Record the bin merging information with Equation (7);
 Apply Equation (8) to every pixel in the image to embed data;
 until $s - 1$ of histogram bins have been expanded in total
 Collect the least significant bits of last 9 pixels in the image;
 Calculate the image histogram excluding the 9 pixels;
 Find the highest histogram bin in the modified histogram;
 Apply Equation (8) to every pixel except the last 9 pixels; previously expanded bins and the collected *LSBs*;
 Replace the *LSBs* of the last 9 pixels with the lastly expanded bin values.

3.3. Proposed Recovery Method

First, the embedded 9 *LSBs* of additional information are extracted from the stego image, obtaining the last embedding position P_S and embedding direction d . Subsequently, using Equation (9), the information embedded in the last round is extracted, including the embedding position P_S and direction d of the previous round, Z_S , Z_m , bk of this round, and the boundary range (I_{min} , I_{max}) of the original image. Then, Z_m is used to confirm whether Z_S was shifted in this round, and Equation (10) is used for recovery. If $Z_m = 1$, Equation (11) is additionally used for recovery. By repeatedly executing the above recovery method, the histogram can be restored to its state before data embedding.

$$b_k = \begin{cases} 1, & \text{if } q_i = P_S \\ 0, & \text{if } q_i = P_S + d \end{cases} \quad (9)$$

$$p'_i = \begin{cases} q_i - d, & \text{if } I_L < q_i < I_R \\ q_i, & \text{else} \end{cases} \quad (10)$$

$$p'_i = \begin{cases} q_i - d, & \text{if } q_i = Z_S \text{ and } lm_e(q_i) = 1 \\ q_i, & \text{else} \end{cases} \quad (11)$$

Next is the recovery description for the pre-processing stage. Since the boundary range I_{max} , I_{min} of the original image is obtained from the last round of extracted data, Equation (12) can then be used to restore the image to its state before histogram stretching. Since the average height of the image will not change due to histogram shifting, Equation (5)

can be reused to calculate the image threshold. In the pre-processing stage, bins higher than average were merged with adjacent bins on the right side. Therefore, by pairing the bins higher than average with the location map (lm_p), the pixels can be accurately restored to the original image, as shown in Equation (13). Finally, simply replacing the 9 LSBs extracted in the first round restores the original image, completing all recovery steps.

$$p_i = \text{round}[(I_{\max} - I_{\min}) \times \frac{p'_i - I_{\max}}{L_{\max} - L_{\min}} + I_{\min}] \quad (12)$$

$$p_i = \begin{cases} p'_i - 1, & \text{if } H(p'_i) > T \text{ and } lm_p(p'_i) = 1 \\ p'_i, & \text{else} \end{cases} \quad (13)$$

Since all histogram modifications are recorded through auxiliary information and location maps, the proposed recovery process can accurately reconstruct the original image without information loss.

The recovery process extracts hidden information and restores the original image losslessly by reversing the embedding and preprocessing operations as shown in Algorithm 3.

Algorithm 3: Proposed image recovery process

Input: The Contrast-enhanced image, denoted by I'

Output: Original image, denoted by I

Parameter: Number of the histogram bin to be expanded (i.e., s)

Collect the LSBs of the last 9 pixels in I' to know last embedded bin values;

Calculate the image histogram excluding the last 9 pixels;

Extract the data embedded in the known bins by using Equation (9);

Carry out the histogram shrinkage with Equation (10) and Equation (11);

Obtain the 9 LSBs values from the extracted data and write them back;

Obtain the value of s and other bin values from the extracted data;

Calculate the image histogram including the last 9 pixels;

For each of the extracted bin values do

Extract the data embedded in the corresponding bins with Equation (9);

Carry out the histogram shrinkage with Equation (10) and Equation (11);

until $s - 1$ of the extracted bin values have been used;

Separate the booking data from the extracted data;

Apply Equation (12) to expand the histogram distribution back to $[I_{\min}, I_{\max}]$

Calculate the average height of the histogram with Equation (5), parameter T ;

For each side of the histogram do

If histogram bins higher than T then

Recover the original image I with the booking data with Equation (13)

3.4. Computational Complexity Analysis

The computational cost of the proposed method is primarily associated with histogram generation, histogram merging, histogram shifting, and pixel scanning operations. Since the histogram contains only 256 grayscale bins, histogram-based operations introduce low computational overhead. The overall complexity is approximately $O(M \times N)$, where M and N denote the image dimensions, making the proposed method suitable for practical image-processing applications. The proposed method combines adaptive preprocessing, brightness-preserving embedding, and reversible recovery to improve embedding capacity and contrast enhancement while maintaining image quality and brightness consistency.

Although the proposed framework introduces an additional adaptive histogram preprocessing stage, the overall computational complexity remains comparable to representative histogram-based CE-RDH methods. The preprocessing, histogram stretching, and brightness-preserving embedding operations are performed sequentially without iterative optimization or complex search procedures, resulting in only a modest computational overhead while providing improved embedding capacity and image quality.

4. Comparison and Analysis

To evaluate the effectiveness of the proposed method, two commonly used public image datasets were used and converted to grayscale images for subsequent analysis and evaluation. These datasets were selected because they contain images with diverse textures, contrast distributions, and structural characteristics, making them suitable for evaluating the effectiveness of CE-RDH methods under different image conditions. These image datasets are:

- (1) USC-SIPI image dataset [18]: 8 grayscale images of size 512×512 .
- (2) Kodak Lossless Color Image Suite [19]: 24 color images of size 768×512 or 512×768 .

The proposed framework contains a single user-defined parameter, S , which represents the total number of embedding rounds. Increasing S allows additional histogram expansions, thereby improving embedding capacity and contrast enhancement. However, excessive embedding rounds inevitably introduces more histogram modifications, which may gradually reduce image quality. Therefore, S directly controls the trade-off between embedding performance and visual quality.

To comprehensively evaluate the proposed method under different embedding conditions, S varied from 10 to 50 with an interval of 10. This range was selected because it covers both low and high embedding scenarios while avoiding excessive histogram distortion that may occur at extremely large embedding rounds. Smaller values emphasize image quality preservation, whereas larger values provide higher embedding capacity and stronger contrast enhancement. Consequently, evaluating multiple values of S enables a comprehensive analysis of the proposed method under different embedding requirements.

Unlike previous methods [6,9,10,13,16], which expand histogram peak pairs during each embedding round, the proposed method expands only a single histogram peak. Therefore, for a fair comparison, the equivalent embedding rounds are represented using $S = 2s$, ensuring that the overall histogram shifting is comparable among different methods.

4.1. Performance Evaluation Methods for the Proposed Method

4.1.1. Image Quality Evaluation Methods

To evaluate the effectiveness of the proposed method, three metrics are used to assess image quality, including PSNR, SSIM [20], and BRISQUE [21]. Since no single metric can fully represent image quality and contrast enhancement performance, multiple objective evaluation metrics are adopted for comprehensive assessment.

PSNR (Peak Signal-to-Noise Ratio) is a traditional image quality assessment metric used to measure the similarity between the stego image and the original image. It is typically measured in dB; the higher the value, the smaller the difference between the two images and the better the quality. When PSNR is above 30 dB, it is difficult for the human eye to detect the difference between the two images. PSNR is calculated based on the Mean Squared Error (MSE) of the image, i.e., the mean of the squared differences in each pixel between the two images. Its main disadvantage is that it only calculates the pixel-level difference without considering the quality perception of the Human Visual System (HVS).

SSIM (Structural Similarity) is an image quality assessment method that mimics the perceptual characteristics of the Human Visual System (HVS) and is highly correlated

with human subjective perception of image quality. It simultaneously considers luminance (Luminance Comparison), contrast (Contrast Comparison), and structure (Structure Comparison) information, attempting to quantify the similarity between images. SSIM values range from 0 to 1; the closer the value is to 1, the higher the structural similarity and the better the quality.

BRISQUE (Blind/Referenceless Image Spatial Quality Evaluator) is a No-Reference Image Quality Assessment (NR-IQA) method in the spatial domain that evaluates quality mainly by analyzing the Natural Scene Statistics (NSS) of the image. Its results are also highly correlated with human subjective perception. BRISQUE values typically range from 0 to 100; the lower the score, the better the image quality. If the image performs exceptionally well, negative values may also appear.

4.1.2. Contrast Enhancement Evaluation Methods

To evaluate the effectiveness of the proposed method, three metrics are used to assess contrast enhancement effects, including RCE, REE, and RMBE [22].

RCE (Relative Contrast Error) is used to measure the contrast change between the stego image and the original image. Contrast is an important visual feature in images; when an image is processed or compressed, changes in contrast affect the clarity and perceived quality of the image. RCE values range from 0 to 1; when RCE is greater than 0.5, contrast has been enhanced, and higher values indicate greater contrast change in the processed image relative to the original. However, excessively high RCE values may cause over-enhancement, making the image look unnatural or distorted. Therefore, appropriately controlling RCE is an important factor in ensuring image quality; RCE is typically maintained slightly above 0.5 to help the image maintain a natural appearance while improving image quality.

REE (Relative Entropy Error) is used to measure the degree of relative entropy change between the stego image and the original image. During the contrast enhancement process, images typically experience an increase in information content, as contrast enhancement also implies greater differences between pixels. Similar to RCE, excessively high REE values will affect image quality, so REE is also maintained slightly above 0.5, allowing image information content to increase with contrast enhancement, but not to a degree that negatively impacts image quality significantly, thereby preserving image visual quality.

RMBE (Relative Mean Brightness Error) is used to measure the brightness change between the stego image and the original image. The average brightness of an image is one of the important factors affecting its visual perception and quality. RMBE values range from 0 to 1; the higher the value, the smaller the brightness change, indicating that the stego image's brightness is closer to the original image. When RMBE equals 1, it indicates that the brightness of the two images is completely identical. Higher RMBE values help ensure that the overall brightness remains stable after contrast enhancement, thereby improving visual quality.

As the embedding rounds increase, the embedding capacity increases almost linearly because additional histogram expansions provide more embedding space. However, repeated histogram modifications gradually reduce PSNR and SSIM while increasing BRISQUE scores, reflecting the inherent trade-off between embedding performance and image quality. Nevertheless, the proposed adaptive histogram preprocessing and brightness-preserving embedding strategy effectively mitigate this degradation, allowing the proposed method to maintain satisfactory visual quality even at higher embedding rounds. Therefore, the parameter *S* can be flexibly selected according to the application requirements, where smaller values prioritize image quality and larger values emphasize embedding capacity.

4.2. Experimental Performance of the Proposed Method

4.2.1. Statistical Results of the Proposed Method

Table 3 demonstrates the effectiveness of the proposed framework under different embedding rounds ($S \in \{10, 20, 30, 40, 50\}$). As the embedding rounds increase, the embedding capacity increases steadily because adaptive histogram bin merging selectively combines dominant histogram bins before embedding, thereby providing a larger number of expandable pixels during each embedding round. Unlike conventional preprocessing methods that determine embedding space according to a predetermined number of embedding rounds, the proposed adaptive preprocessing strategy exploits the histogram distribution more efficiently, allowing additional embedding capacity without introducing excessive histogram disorder.

Table 3. Statistical Average Results of the Proposed Method.

Images	S	RCE	REE	RMBE	BRISQUE	SSIM	PSNR (dB)	Embedded Bits
Kodak (24 images)	10	0.484	0.483	0.973	8.32	0.968	28.64	223,601
	20	0.496	0.502	0.989	8.93	0.968	32.55	356,228
	30	0.514	0.516	0.996	12.03	0.952	31.82	459,576
	40	0.532	0.527	0.996	14.71	0.921	27.64	544,614
	50	0.549	0.535	0.995	17.07	0.882	24.36	621,415
USC-SIPI (8 images)	10	0.499	0.479	0.952	20.65	0.972	26.43	126,241
	20	0.504	0.498	0.971	21.38	0.967	28.40	208,601
	30	0.519	0.511	0.986	23.53	0.954	28.30	273,059
	40	0.536	0.521	0.992	24.46	0.933	27.00	330,765
	50	0.551	0.528	0.992	25.18	0.903	24.20	383,948

Regarding image quality, PSNR and SSIM gradually decrease as S increases because additional embedding operations inevitably introduce more histogram modifications. Nevertheless, the proposed method maintains PSNR above 24 dB and SSIM above 0.88 even at $S = 50$, indicating that the structural information of the original image is effectively preserved despite the increased embedding capacity. This demonstrates that the proposed preprocessing and brightness-preserving embedding strategies successfully balance embedding performance and visual quality.

The proposed method also exhibits excellent brightness preservation. Although RMBE is slightly reduced during the initial embedding rounds due to preprocessing, it rapidly approaches 1.0 as embedding progresses. This behavior results from the adaptive brightness-preserving embedding mechanism, which dynamically selects the embedding direction according to the current image brightness, thereby compensating for brightness deviations introduced during histogram modification. Consequently, brightness consistency is maintained without sacrificing embedding capacity or contrast enhancement.

Overall, the experimental results indicate that the proposed framework effectively balances embedding capacity, contrast enhancement, and visual quality by jointly optimizing histogram preprocessing and adaptive embedding, demonstrating its superiority over conventional CE-RDH approaches.

The proposed framework consists of three complementary components. Adaptive histogram bin merging improves embedding capacity while preserving pixel order, histogram stretching enhances image contrast, and brightness-preserving embedding maintains brightness consistency through adaptive embedding direction selection. Together, these components enable the proposed framework to achieve high embedding capacity while preserving image quality.

4.2.2. Visual Results of the Proposed Method

The proposed method was applied to 24 images from the Kodak image dataset and 8 images from USC-SIPI, performing $S = 50$ rounds of contrast enhancement. Figure 8 shows the original image on the left and the enhanced image on the right. From the comparison group in Figure 8, it can be seen that the proposed method can indeed effectively enhance the contrast of the original image. Parts of the original image that are blurry or unclear become clearer in details and features through contrast enhancement, improving image recognizability. Furthermore, even at high embedding rates, the visual results do not show any degradation or impact, preserving various features and details of the original image well. The comparison group in Figure 9 further zooms in on local regions of the image, with the original image on the left and the enhanced image on the right. From the framed portion of Goldhill, it can be observed that the color of the bricks in the original image is relatively uniform, while the contrast-enhanced image on the right shows that the contrast has been clearly widened, with the color depth differences between different bricks being highlighted, and clearer outlines at the brick seams. From the framed portion of Kodak-23, it can be observed that the feather colors in the original image are relatively uniform and difficult to distinguish, while the contrast-enhanced image on the right makes the details clearer, with shadows more prominent, allowing different parts of the feathers to be more easily distinguished. Through these comparisons, the effect of the contrast enhancement method in improving image detail and clarity can be clearly seen.



Figure 8. Visual comparison results using the proposed method.

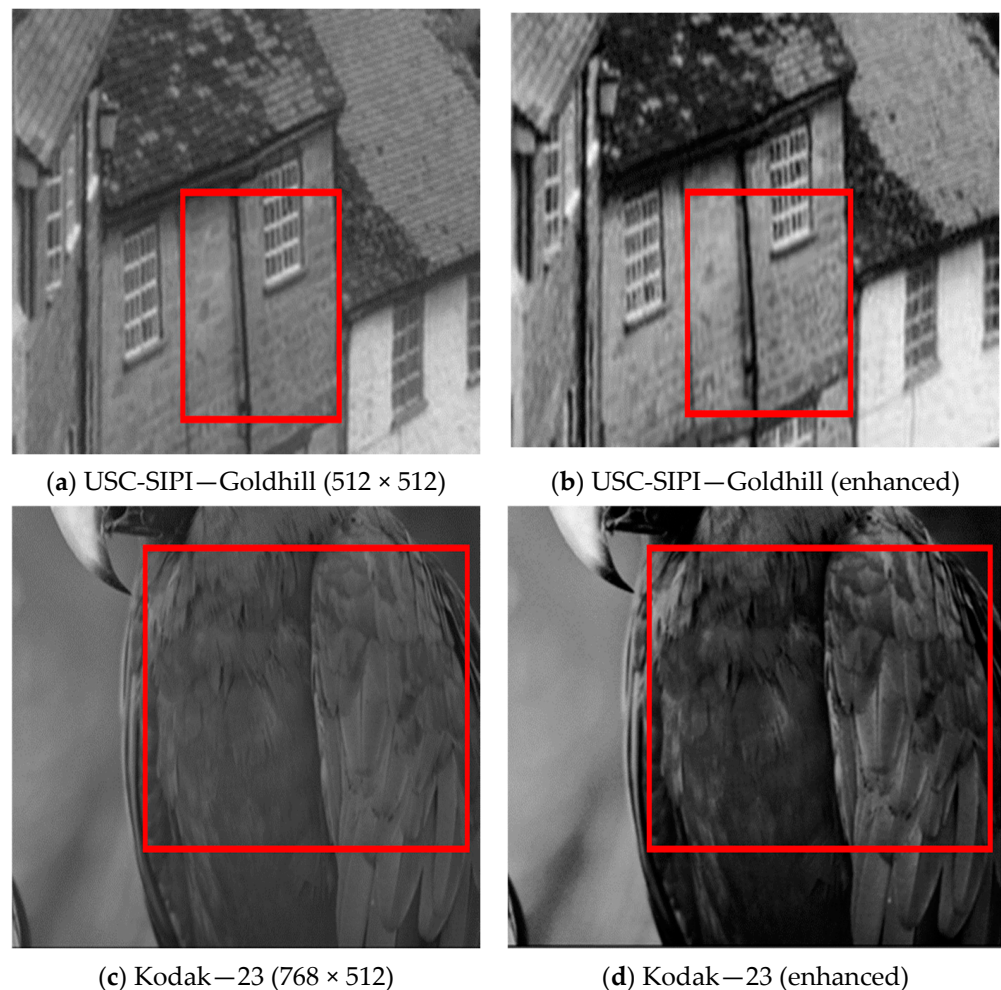


Figure 9. Visual comparison results using the proposed method (local regions).

4.3. Experimental Comparison of the Proposed Method

4.3.1. Statistical Comparison of the Proposed Method

To better demonstrate the performance of the proposed method, this section compares it with several previously introduced methods [6,9,10,13,16], using the six metrics introduced in Sections 4.1.1 and 4.1.2 for evaluation. The experiments use the two image datasets mentioned above, Kodak and USC-SIPI, comparing different methods under the same number of embedding rounds, with $S = 20, 30, 40$, and 50 for testing. Note that method [9] cannot be applied to some images in the Kodak dataset at $S = 50$, so $S = 50$ statistical data for the Kodak dataset are not listed.

First, from Tables 4 and 5, the trends of RCE and REE can be observed: the data of all methods show a gradually increasing trend as S increases. This indicates that all methods do continuously enhance image contrast and increase the information content of the image as data is embedded. However, higher contrast may lead to over-enhancement, causing image distortion. For example, the RDHCE method [6] achieves the highest contrast enhancement in most cases, but correspondingly, its image quality is also the worst (BRISQUE, SSIM, PSNR). Therefore, in the evaluation of RCE and REE, it is only necessary to ensure that image contrast increases with the amount of embedded data, without blindly pursuing high values.

Table 4. Statistical Average Results of Different Methods (24 Kodak Images).

<i>S</i>	Methods	RCE	REE	RMBE	BRISQUE	SSIM	PSNR (dB)
20	Wu et al. [6]	0.544	0.528	0.985	16.65	0.902	24.89
	Wu et al. [13]	0.539	0.529	0.984	15.42	0.914	24.70
	Wu et al. [9]	0.537	0.528	0.982	14.00	0.928	25.02
	Wu et al. [16]	0.539	0.534	0.982	13.79	0.921	24.85
	Lee et al. [10]	0.534	0.526	0.984	13.59	0.938	26.36
	Proposed	0.496	0.502	0.989	8.93	0.968	32.55
30	Wu et al. [6]	0.560	0.535	0.976	20.57	0.831	21.34
	Wu et al. [13]	0.555	0.535	0.975	19.84	0.843	21.53
	Wu et al. [9]	0.550	0.533	0.970	15.08	0.890	22.27
	Wu et al. [16]	0.555	0.541	0.974	15.59	0.871	21.74
	Lee et al. [10]	0.546	0.531	0.974	14.90	0.901	23.24
	Proposed	0.514	0.516	0.996	12.03	0.952	31.82
40	Wu et al. [6]	0.572	0.539	0.966	27.19	0.743	18.94
	Wu et al. [13]	0.569	0.539	0.966	26.37	0.755	19.12
	Wu et al. [9]	0.559	0.535	0.962	16.13	0.865	20.88
	Wu et al. [16]	0.570	0.546	0.964	16.49	0.825	19.68
	Lee et al. [10]	0.552	0.534	0.962	15.40	0.872	21.35
	Proposed	0.532	0.527	0.996	14.71	0.921	27.64
50	Wu et al. [6]	0.581	0.542	0.954	35.93	0.638	16.76
	Wu et al. [13]	0.578	0.541	0.952	34.71	0.653	16.98
	Wu et al. [16]	0.580	0.549	0.951	17.42	0.797	18.36
	Lee et al. [10]	0.552	0.535	0.950	15.74	0.856	20.16
	Proposed	0.549	0.532	0.995	17.06	0.882	24.36

Except for the proposed method, RMBE of all other methods shows a downward trend as *S* increases, indicating that without brightness preservation techniques, the brightness performance of images diverges further from the original image as the data hiding process progresses. Since the proposed method incorporates brightness preservation, the image adaptively self-corrects during embedding, making the image brightness approach the original image and ensuring that the image structure and features are not damaged by over-enhancement. When *S* exceeds 40, RMBE values can stably remain above 0.99, which is almost completely consistent with the brightness of the original image and significantly higher than other methods, highlighting the advantages brought by incorporating brightness preservation in the proposed method. Finally, for the three image quality metrics BRISQUE, SSIM, and PSNR, as *S* increases, the image quality of all methods decreases, indicating that more modifications are made to the image as the amount of embedded data increases. In terms of BRISQUE performance, the proposed method is consistently relatively low, performing even better when *S* is low. The proposed method also significantly outperforms other methods in SSIM and PSNR, showing that while enhancing contrast, it can effectively preserve image structure and features, suppressing noise, and further demonstrating the effectiveness of the proposed method in maintaining image quality and brightness. In summary, the proposed method consistently achieves the best brightness preservation and superior image quality while maintaining competitive contrast enhancement performance. These results confirm that the proposed brightness-preserving embedding strategy effectively mitigates the over-enhancement problem commonly observed in existing CE-RDH methods.

Table 5. Statistical Average Results of Different Methods (8 USC-SIPI Images).

S	Methods	RCE	REE	RMBE	BRISQUE	SSIM	PSNR (dB)
20	Wu et al. [6]	0.548	0.526	0.989	23.54	0.920	25.05
	Wu et al. [13]	0.547	0.525	0.989	23.41	0.927	25.09
	Wu et al. [9]	0.543	0.526	0.987	22.74	0.936	25.54
	Wu et al. [16]	0.545	0.530	0.990	22.64	0.932	25.45
	Lee et al. [10]	0.545	0.525	0.985	24.65	0.931	24.97
	Proposed	0.504	0.498	0.971	21.38	0.967	28.4
30	Wu et al. [6]	0.567	0.533	0.983	27.89	0.852	21.72
	Wu et al. [13]	0.565	0.532	0.983	27.0	0.860	22.01
	Wu et al. [9]	0.555	0.533	0.980	23.48	0.903	23.27
	Wu et al. [16]	0.561	0.538	0.985	23.47	0.893	22.94
	Lee et al. [10]	0.562	0.531	0.977	24.62	0.889	22.27
	Proposed	0.519	0.511	0.986	23.53	0.954	28.30
40	Wu et al. [6]	0.577	0.535	0.971	34.89	0.755	19.27
	Wu et al. [13]	0.571	0.534	0.963	33.21	0.770	19.23
	Wu et al. [9]	0.565	0.537	0.971	23.93	0.876	21.67
	Wu et al. [16]	0.573	0.543	0.970	24.25	0.856	20.97
	Lee et al. [10]	0.569	0.534	0.971	24.56	0.866	20.97
	Proposed	0.536	0.521	0.992	24.46	0.933	27.00
50	Wu et al. [6]	0.581	0.537	0.966	44.38	0.647	17.28
	Wu et al. [13]	0.571	0.535	0.952	40.56	0.675	17.44
	Wu et al. [9]	0.572	0.538	0.967	24.30	0.853	20.76
	Wu et al. [16]	0.583	0.546	0.962	24.69	0.822	19.69
	Lee et al. [10]	0.570	0.534	0.962	24.45	0.858	20.36
	Proposed	0.551	0.528	0.992	25.18	0.903	24.20

4.3.2. Embedding Capacity Comparison of the Proposed Method

In addition to maintaining good image quality, embedding capacity is also a very important metric. After all, achieving high quality by restricting embedding capacity would greatly limit the usability of data hiding. Therefore, a good method needs to perform well not only in image quality but also in embedding capacity, typically calculated by the total number of embedded bits or the amount of information hidden in the image.

To effectively evaluate the embedding capacity of the proposed method, it is compared with the OPHBE [9] method, which also employs order-preserving pre-processing. Several images are selected from the Kodak and USC-SIPI datasets for evaluation in Table 6. It can be found that the proposed method demonstrates higher embedding capacity across different images, reflecting that appropriately selecting higher bins to merge with each other during the pre-processing stage can indeed effectively improve the embedding capacity of the image. These results demonstrate that the proposed adaptive histogram bin-merging strategy effectively increases embedding capacity while maintaining the advantages of order-preserving preprocessing.

Table 6. Total Embedding Capacity Comparison Results of Different Methods.

Images	Methods	S	Embedded Bits
Kodak—13 (768 × 512)	Wu et al. [9]	53	464,769
	Proposed		500,653
Kodak—23 (768 × 512)	Wu et al. [9]	52	461,690
	Proposed		552,459

Table 6. Cont.

Images	Methods	S	Embedded Bits
Kodak—24 (768×512)	Wu et al. [9]	48	396,643
	Proposed		571,335
Goldhill (512×512)	Wu et al. [9]	57	293,808
	Proposed		331,202

4.3.3. Visual Quality Comparison of the Proposed Method

This section compares the visual performance of the images. The main comparison targets are two CE-RDH methods that do not use order-preserving pre-processing [6,13], and two CE-RDH methods that also employ order-preserving pre-processing [9,10]. When $S = 50$, it can be found that the contrast of images from all methods increases after data embedding, as shown in Figure 10.



Figure 10. Visual comparison results of different methods ($S = 50$). From left to right and top to bottom: original image, the method of Wu et al. [6], the method of Wu et al. [13], the method of Wu et al. [9], the method of Lee et al. [10], and the proposed method.

Next, we further zoom in the upper right corner of the image. CE-RDH methods without order-preserving pre-processing all introduce obvious artificial distortions that cause significant damage to image quality. The enhanced images produced by the CE-RDH methods with order-preserving improvements [9,10] and the proposed method do not exhibit this type of distortion as shown in Figure 11. Preserving pixel ordering is very important for this type of method that modifies pixels to achieve contrast enhancement, ensuring that edges, textures, and other important features in the image are not distorted or displaced after contrast enhancement, thereby achieving better image quality.

The selected representative images include different visual characteristics, such as smooth regions, rich textures, and edge structures, enabling a comprehensive qualitative evaluation of the proposed method. The visual comparisons demonstrate that the proposed framework consistently preserves brightness and structural details while effectively enhancing image contrast across these representative image characteristics.

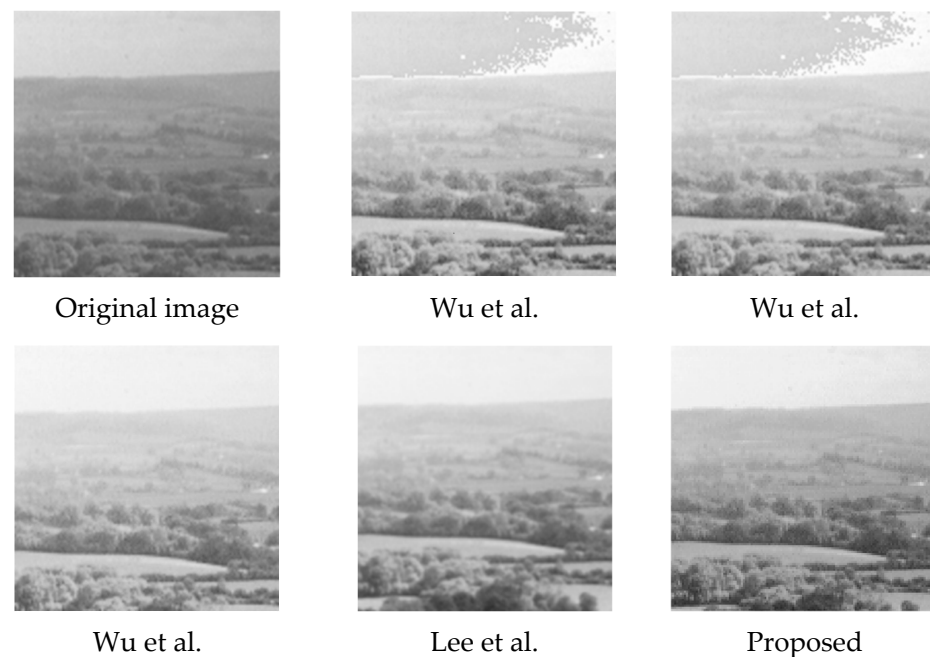


Figure 11. Local visual comparison results of different methods ($S = 50$). From left to right and top to bottom: original image, the method of Wu et al. [6], the method of Wu et al. [13], the method of Wu et al. [9], the method of Lee et al. [10], and the proposed method.

5. Conclusions

This study reviews the evolution of recent contrast enhancement-based reversible data hiding methods and proposes a novel reversible data hiding method for image contrast enhancement. The main features are increasing capacity through order-preserving pre-processing and embedding data with brightness preservation to enhance image contrast for better visual results. From the experimental comparison results in Section 4, the proposed method achieves superior brightness preservation while maintaining competitive image quality and embedding capacity. In particular, the proposed method maintains RMBE values above 0.99, SSIM values above 0.88, and PSNR values above 24 dB under high embedding rounds. These results verify that the proposed method effectively balances embedding capacity, contrast enhancement, brightness preservation, and image quality under different embedding rounds, demonstrating strong practical applicability. It also provides new research directions to further promote the development and application of data hiding technology. Overall, the experimental results confirm the effectiveness of the proposed method in simultaneously achieving high embedding capacity, brightness preservation, and visual quality.

In the order-preserving pre-processing process proposed in this study, the space requirements for data embedding were not considered; instead, the histogram is adjusted during the data embedding stage. Therefore, future research may investigate adaptive preprocessing strategies that generate only the required embedding space, potentially further improving image quality and visual performance. Recent studies have explored automatic contrast enhancement techniques for reversible data hiding applications [28]. In addition, if this method is to be applied to medical images, background segmentation and local contrast enhancement techniques [29] can be incorporated into the pre-processing process to extract the ROI (Region of Interest) for application. Furthermore, simultaneous image quality enhancement and reversible data hiding [30,31] frameworks may provide additional directions for improving both embedding performance and visual quality. This

would make the proposed method more flexibly applicable, satisfying the needs of different situations and demonstrating the practicality and functionality of the proposed method.

Although the proposed framework demonstrates superior embedding capacity, brightness preservation, and image quality, several limitations remain. The current method has been evaluated using grayscale images and histogram-based CE-RDH techniques, and its performance has not yet been investigated for color images, high-resolution images, or domain-specific applications such as medical image enhancement. Furthermore, the parameter S is manually specified according to application requirements rather than being automatically optimized. Future research will focus on extending the proposed framework to color image reversible data hiding, adaptive parameter selection, region-aware embedding strategies, and medical image applications while further improving computational efficiency and perceptual image quality.

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