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Image Degradations and Processing Challenges Under Uneven Illumination: A Narrative Review

Zainab Khalid Younis [1,*], Mohd Shafry Mohd Rahim [2], and Farhan Bin Mohamed [2]

[1] Department of Computer Science, College of Computer Science and Mathematics, University of Mosul, Mosul, Nineveh, IRAQ

[2] Department of Computer Science, Faculty of Computing, Universiti Teknologi Malaysia (UTM), Skudai, 81310, Johor Bahru, MALAYSIA

***Corresponding email:** zainab.younis@uomosul.edu.iq

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Abstract: Image processing is considered a crucial element in various applications and technologies, such as photography, surveillance and computer vision. Enhancing image appearance and visual quality in photography technique is essential to generate clear, detailed and aesthetically pleasing images. One of the most challenging aspects in image processing fields is the to deal with is uneven illumination and low-light conditions. Despite the development of camera technology and manufacturing, low-light environments usually result in images that suffer from noise, low brightness, and pale colors and low contrast. To enhance and improve the quality for such images needs a complicated process and several visual corrections in characteristics. Adjust and balance the brightness and contrast in image are essential to reveal hidden features and avoid overexposing in bright region in images. Color enhancement is crucial as well; pale or dull images must be enhanced to be more realistic and vivid to meet user desire. Furthermore, noise reduction presents a major challenge, especially in dark regions where noise is predominant and can hide important features. However, improving illumination, colour appearance, and noise reduction together while preserving important image details remains challenging. This article presents a narrative review of common image degradations in low-light images and addresses the main enhancement challenges. It also examines the strengths and limitations of existing enhancement methods and highlights the main research gaps to support future research under challenging lighting conditions.

Keywords: Uneven illumination, Image enhancement, Low-light image enhancement, Image denoising, Colour enhancement

1. Introduction

Image processing is essential in various fields due to its ability to manipulate and analyse visual information. [1, 2] The main reason for introducing image processing into numerous fields and technologies is the need to produce better image quality, as perfect image quality cannot be achieved at a single capture level. [3–5] The term "image degradation" describes the degradation of image quality while capturing and recording visual information associated with cameras and capture systems. Many factors that lead to reduced image quality affect the fidelity and accuracy of captured images [6]. Limitations in camera sensors' dynamic range, spatial resolution, and noise can also cause damage [7]. Quantization errors and artifacts introduced by the acquisition system (including the analog-to-digital conversion process) can affect the accuracy of the recorded data.

Uneven illumination in images is the source many challenges and difficulties to computer vision applications and image processing [10]. Uneven illumination means some image parts appear well-illuminated while others appear darkened or with low illumination [11]. Various factors, such as uneven lighting, shadows, reflections, and an environment with insufficient lighting, could cause this issue. The main contributing factors are uneven environmental lighting and shadows [12]. Uneven illumination should be distinguished from insufficient overall lighting: an unevenly illuminated image contains spatial brightness differences, whereas a low-light image is captured under inadequate overall illumination [9]. An image might demonstrate both conditions; however, they represent different types of image degradation, Image noise refers to unwanted random or structured variations introduced during image acquisition or processing. Colour degradation refers to changes in colour representation that affect the accuracy and natural appearance of an image.

In this regard, uneven illumination can make it difficult to accurately notice and interpret the content of an image because it has various implications for visual features. The details in this case are affected by different distortions. These distortions can affect colour representation, reduce the visibility of details in shadow and highlight regions, and make noise more noticeable when dark areas are brightened [19]. As these effects are closely related, increasing image brightness does not necessarily lead to an improvement in overall image quality [18]. Likewise, some algorithms may generate halos, artifacts, or unnatural shadows around the edges, as these distortions can reduce the visual quality and should be avoided [25]. Moreover, balancing the illumination enhancement of details while avoiding over-sharpening or over-smoothing is challenging, and preserving a realistic appearance is crucial [26]. Furthermore, some algorithms may involve high computational costs, which is undesirable as many applications have limited hardware resources [27].

To address these challenges, several methods have been developed, including histogram-based enhancement, Retinex-inspired illumination correction [21], and learning-based methods [20], in addition to specialized denoising and colour enhancement methods [33]. While each study reports improvements in specific image- attributes and quality, their objectives, evaluation conditions, and metrics differ. This makes it difficult to compare how different studies balance image quality, colour fidelity, detail preservation, and computational cost. The focus of the present narrative review is therefore to synthesise the strengths, limitations, and interactions of representative published approaches, rather than to claim a newly developed algorithm or new experimental findings. Although existing image enhancement methods can improve illumination, colour appearance, and noise reduction, achieving these improvements together while preserving fine image details and maintaining reasonable computational complexity remains challenging. This narrative review examines the strengths and limitations of existing enhancement methods and highlights the main research gaps related to these challenges.

2. Review Approach and Scope

This article delivers a narrative reviews of selected studies on image enhancement under uneven illumination, colour correction, and image denoising. These studies are discussed based on the image degradations they address and the strengths and limitations of their methods. It also discusses that how chosen methods enhance and improve image quality, beside the challenges that arise when image degradations occur separately or all together. Furthermore, correcting one image degradation could led to affect other visual properties of image. For instance, when increase brightness in dark regions this reveal hide noise and make it more visible, while attenuating noise may lead to the loss of fine details. Also, each of the reviewed study uses different datasets of images, experimental settings, and evaluation metrics, this causing difficult to compare their outcome and result. Thus, the outcomes are discussed in the context of each study to identify common limitations and challenges.

3. COMMON IMAGE DEGRADATIONS

Captured images are only sometimes obtained to be perfect in quality as degradation may be introduced due to circumstances that are evitable in some situations and inevitable in most situations [8]. One inevitable degradation of interest in most situations is uneven illumination [9]. Uneven illumination in images can pose challenges for various applications related to computer vision and image processing [10]. Uneven illumination means some image parts appear well-illuminated while others appear darkened or with low illumination [11].

Various factors, such as uneven lighting, shadows, reflections, and an environment with insufficient lighting, could cause this issue. The main contributing factors are uneven environmental lighting and shadows [12]. In most cases, people take their photos in an unprepared environment, where they see a nice scene and capture an image of it. They do not consider the existence of shadows or the illumination condition in that environment, ending up with non-uniform images. Figure 1 displays various images with an uneven illumination effect. As observed, the unevenly illuminated images have bright and dark areas, are not pleasant to the observer, the image featured is obscured in the darkened parts, the colours appear inaccurate, and the overall appearance could be more satisfying. Images with this artifact can be less significant, as it affects different fields of image processing. Regarding object recognition and segmentation [13], the look of items in an image can be affected by uneven illumination, making it difficult for computer vision systems to identify and segment objects precisely.

Different illumination can cause one to misread the outlines and borders of objects. In feature extraction, some aspects of an image may be hidden or overexposed due to uneven illumination. As a result, variations feature representation throughout the image may affect performance of feature extraction methods. As for colour analysis [14], uneven lighting can cause colour intensity and hue differences in colour-based applications like image analysis or classification.



Figure 1: Different unevenly illuminated images.

As a result, this makes it challenging to do an accurate analysis using only colour information. Regarding image matching [15], the performance of image-matching algorithms can be impacted by uneven illumination because varied lighting conditions might cause an object to appear differently. Importantly, this is especially important for applications such as object recognition and picture retrieval. Additionally in augmented reality [16], uneven illumination and low lighting can impact how well virtual objects blend into the real world in applications where real-world scenes are enhanced with virtual features. As for object ambiguity [17], ambiguity can be introduced into object representations due to uneven illumination. It can be difficult to distinguish different pieces in a scene when parts of an object blend into the background or nearby surfaces due to shadows and lighting. In terms of shape perception [18], uneven lighting can impact how an object's shape is seen in the image. Moreover, size and shape of an objects can be warped by optical illusions caused by shadows and changes in illumination.

Generally, people usually capturing photos in unplanned settings without considering shadows or lighting conditions, leading to non-uniform images. In such cases, image details are affected by different distortions. The first is poor colours [19], as variations in brightness across the image can affect how colours are represented, in that shadows and highlights may not accurately represent the true colours of the scene. The second is highlight and shadow distortions [20], in that certain elements may be obscured or overemphasized by bright or dark patches, which may impact how the scene is generally perceived. The third is image noise [21], as the noise exists in the darkened parts of the image, and once equalized, the noise will appear, making the image undesirable to the observer. Also, this effect can cause misleading analysis [22], as it is possible for analysis based on colour, texture, or shape to be compromised, leading to conclusions about the underlying scene that are false. Figure 1 shows the degradations mentioned above.

4. PROCESSING CHALLENGES

Illumination correction aims to improve the visibility of poorly illuminated regions. However, increasing brightness does not always improve the overall image quality because other image properties may also be affected. Low-light images are frequently distorted by noise, especially in the dark parts of the image. As a result, brightening dark regions, lead to make the existing noise more noticeable [23]. Illumination enhancement can also affect colour representation [10] or introduce halos and unnatural transitions around image edges [25]. Preserving fine details while improving brightness is another challenge [26]. In addition, the computational requirements of some enhancement methods can limit their use on devices with restricted processing resources [27].

As for image noise, image denoising is usually applied, which is the process of attenuating noise from an image and producing better visual details [28]. Maintaining sharp edges and details is crucial for denoising since many techniques may inadvertently blur the image while denoising it, leading to a loss of essential structural information [29]. In addition, the core challenge in image denoising is to reduce the noise while preserving essential details and avoiding over-smoothing the processed image, since some denoising algorithms tend to remove non-noise image information [30]. For colour images, denoising should also preserve important colour and structural information [32]. Besides, preserving image details, processing speed is also important, especially when denoising methods are used in real-time applications [31]. Regarding inadequate colour presentation, image colour enhancement algorithms are usually applied to adjust the colour representation and improve saturation and overall appearance to enhance the image's visual appeal [33]. However, increasing colour saturation does not reflect a better image quality. Also, over enhancement give a result with unnatural colours [34]. Therefore, the main difficulty rise in enhancing image colour appearance while maintaining a reasonable balance between saturation and naturalness. Existing methods often focus on one degradation independently; however, these degradations are interrelated, where illumination enhancement can reveal or amplify noise, denoising can affect fine details, and colour enhancement can influence the natural visual appearance. Thus, improving one image-quality attribute may affect another making the overall enhancement process more difficult. Accordingly, the performance of an image enhancement method should be considered in terms of illumination correction, noise attenuation, colour fidelity, detail preservation, and computational requirements. The following section examines the reported strengths and limitations of existing approaches in relation to these challenges.

5. CRITICAL DISCUSSION OF EXISTING ENHANCEMENT APPROACHES

This section presents a narrative discussion of the strengths and limitations of several illumination correction, colour enhancement, and denoising methods, also, the analysis in this section based on several selected methods in image enhancement focusing on visual quality, detail preservation, and computational requirements. For illumination correction, histogram-based methods, including exposure-based multi-histogram equalization [11], redistribute image intensities to improve contrast under uneven illumination. However, over-enhancement of dark regions may affect the natural balance of the image. Rahman et al. [9] developed a CNN-assisted model that used for correcting uneven illumination, while Retinex-decomposition methods [21] address illumination variations by modelling illumination and reflectance. In addition, other approaches consider lighting conditions, which involve suppression of strong-light regions [36]. Across existing approaches, colour shifts, halos, and sensitivity to parameter settings remain important considerations [25, 26]. For example, Younis et al. [39] introduced the refined single-scale Retinex (RSSR) method, which processes the value channel of the HSV colour space. The study compared RSSR with ten other algorithms using runtime and three image-quality measures. The RSSR developed method contain comparison of six-images, it reported the lowest average lightness order error (LOE: 151.32) among the compared methods and an average runtime of 2.51 s. However, the gamma parameter must be selected manually for each image, limiting the method's suitability for fully automated processing [39]. Figure 2 shows the comparison scored by RSSR method [39]. The figure, differences of the output's images are visible in the treatment of bright regions, darker vegetation, and scene details, and it is an illustration example of RSSR result outcomes.

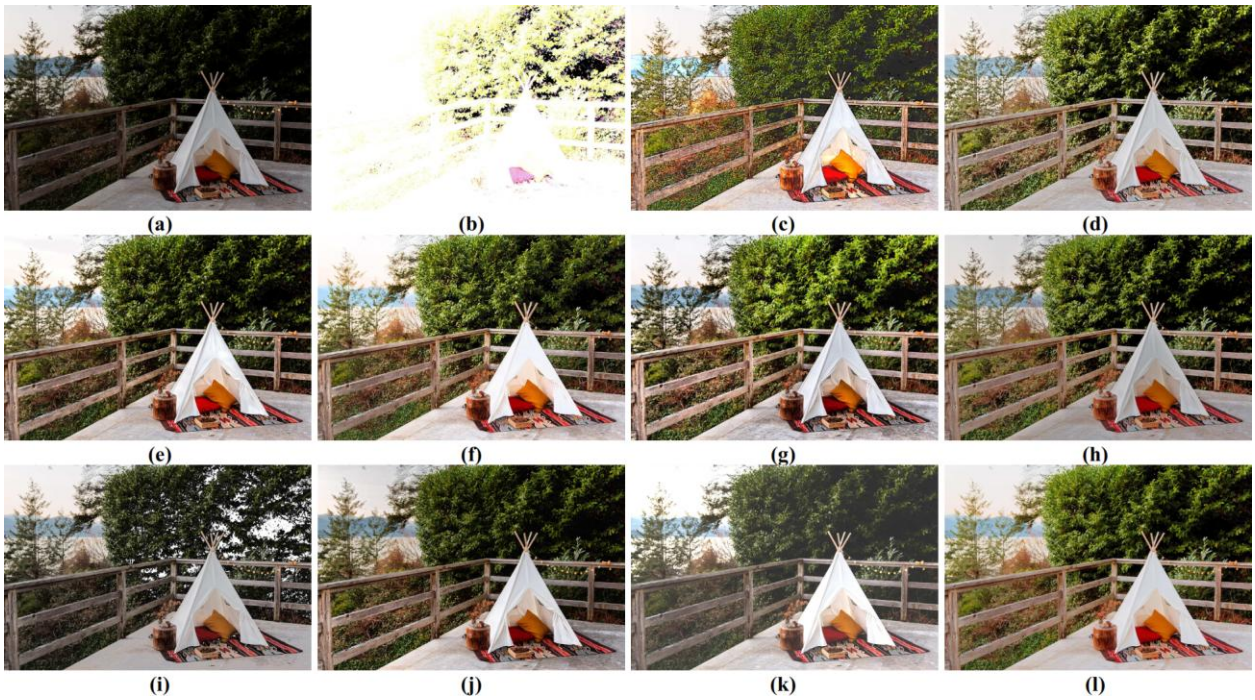


Figure 2: Comparison of illumination enhancement methods: (a) original image; (b–k) results of ten comparison methods; (l) RSSR result [39].

In addition, learning-based enhancement approaches [8, 20, 23, 24, 35] have been explored to address complex lighting conditions and improve image appearance. Some methods use learned features to reconstruct poorly illuminated regions. Therefore, evaluating performance of such methods relies on first the training data and second on their ability to generalize to images outside the training conditions. For practical applications, memory, processing capacity, and power consumption are important considerations, particularly on mobile and edge devices. Therefore, evaluations should consider both the computational resources required for training and those needed to apply a trained model. Regarding colour degradation, colour enhancement methods [33, 34, 37, 38] aim to improve colour appearance while avoiding oversaturation and colour shifts. In this regard, improving deficient colour representation, Younis et al. [40] proposed the automated Chroma Booster (CB) method to improve colour vibrancy. CB processes saturation and lightness separately in HSL and applies further processing after conversion to RGB. The CB method compared with eight methods via three colour-quality measures and runtime. The output results and experiments, CB presents an average colourfulness factor (CF) of 66.78 and an average runtime of 4.02 s [40]. The authors also identify limitations when input images are already colour-rich or

relatively dark. These cases show why stronger colour enhancement does not always produce a more natural image [40]. Figure 3 presents the colour-enhancement comparison by CB method [40]. It noticed that variations in colour saturation and tonal appearance can be observed in the flowers, butterfly, and background. Figure 3, provide a visual comparison, beside the quantitative measurements that stated in this study.

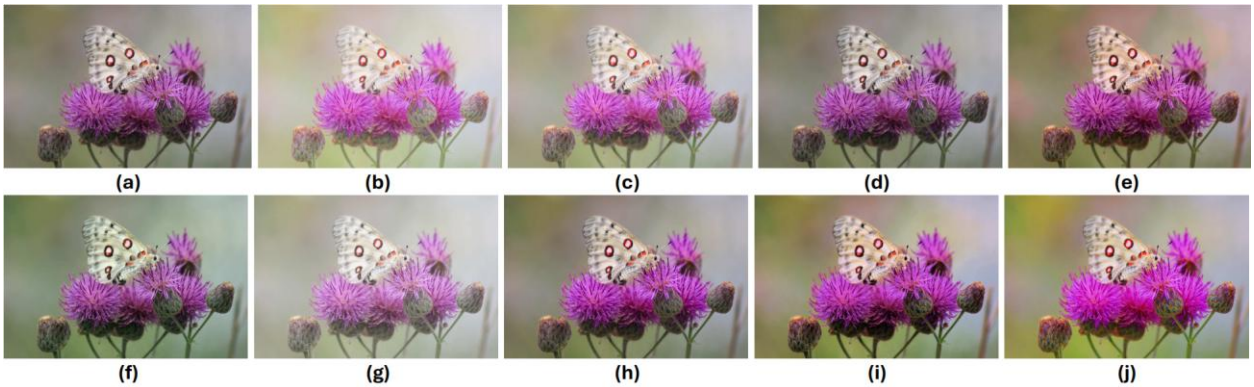


Figure 3: Comparison of colour enhancement methods: (a) original image; (b–i) results of eight comparison methods; (j) CB result [40].

Regarding noise attenuation, denoising methods include non-local means [29], learning-based restoration [30], hardware-oriented filtering [31], and approaches that model colour and structural information [28, 32]. Theis's methods could attenuate unwanted noise in image regions, however excessive smoothing cause remove and affecting edges and fine textures. Beside some methods computationally expensive and require long processing time or specialized hardware. A meaningful comparison should therefore consider the amount of noise removed alongside the details retained and the computational cost.

Table 1: Qualitative comparison of representative image enhancement approaches.

#	Methods	Strength	Key limitation
1	Histogram-based [11]	Improves contrast through intensity redistribution.	Over-enhancement may disturb the balance between bright and dark regions.
2	Retinex-based [21, 39]	Addresses spatial illumination differences; RSSR processes the HSV value channel.	Halo or colour artifacts remain possible; RSSR uses manual gamma selection.
3	Other illumination correction [9, 25, 26, 36]	Handles non-uniform exposure, brightness balance, or strong-light regions.	Results depend on scene conditions and the control of visual artifacts.
4	Learning-based [8, 20, 23, 24, 35]	Learns mappings for challenging illumination and image appearance.	Dependence on training data, generalisation, and computational resources.
5	Denoising [28–32]	Reduces unwanted noise while aiming to preserve image structure.	Fine-detail loss, residual noise, or hardware and runtime constraints.
6	Colour enhancement [33, 34, 37, 38, 40]	Improves colour vibrancy; CB combines HSL and RGB processing.	Oversaturation or colour shifts; CB is limited on colour-rich or dark inputs.

The studies in Table 1 use different datasets, evaluation measures, and experimental settings. Their results are therefore informative about individual methods, but they do not establish a direct performance ranking across all three-degradation type. On the practical side, adjusting illumination is essential for improving image clarity, especially in difficult lighting conditions. For applications such as mobile photography, the useful outcome is not simply a brighter or more colourful image. Enhancement should also preserve a natural appearance, control visible noise, and remain feasible on the intended hardware. These considerations identify a continuing need for studies that evaluate the combined effect of illumination correction, denoising, and colour enhancement, rather than assessing each degradation in isolation.

6. Conclusion

In conclusion, digital images enhancement that degraded by uneven illumination, low-light conditions, noise, and colour distortion remain a substantial challenge. Therefore, the need for effective image enhancement methods is vital to improve the whole visual quality whereas keep maintain important image details. Although their methods required high computational cost and limited the practical use, they can apply in several and various imaging applications. Overall, methods that discussed such illumination correction, colour enhancement, and denoising have different strengths and limitations. Furthermore, enhancing one attribute of

image quality can also affect others, including colour intensity, visible noise, and detail preservation. Finally, as future work, developing different image enhancement methods and integrated them together can address these degradations and introduce low computational cost and requirements which make it more reasonable. Also, further comparative evaluations using common datasets and evaluation metrics could help assess the trade-offs among visual quality, detail preservation, and computational efficiency.

CONFLICT OF INTEREST

"**The authors declare no conflict of interest**".

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