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A robust framework for visibility enhancement of foggy images

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ABSTRACT

This paper presents a robust framework for visibility enhancement of images degraded by foggy weather conditions. The proposed defogged algorithm is developed by the combining of modified visibility restoration approach and S-shaped transfer function for foggy weather degraded images. The proposed defogged algorithm works in two steps: in first step trilateral filter based visibility restoration algorithm is used for visibility and smoothness of the degraded images. Further in the second step S-shaped transfer function is used for contrast enhancement of the foggy images. The image quality metrics of proposed defogged and other existing visibility restoration algorithms are evaluated in terms of Fog Reduction Factor (FRF), Measure of Enhancement Factor (EMF) and blind parameter (η) on different foggy image databases. We demonstrate the strength of proposed defogged algorithm by estimation the thickness of fog in the input image as well as the output image. Finally, the simulation results and visualisation of defogged images indicate that the proposed defogged algorithm is highly effective and efficient for visibility enhancement of foggy images.

1. Introduction

In natural and practical scenario the light reflected from the object is scattered in the atmosphere, due to the presence of particles like dust, mist, fumes, water droplets and some other means deflect the light from its original path of propagation. Due to this effect the images contains low contrast, faint in color and lower visibility [1]. So fog removal algorithm is highly required in commercial images, computational photography and many vision based applications. Removing fog from degraded image provides a significant scene of visibility for image analysis from a low level to high level. To improve the visibility and contrast enhancement of foggy images we have proposed a modified visibility restoration algorithm to obtain the smooth fogless image [2,3] and S-shaped transfer function for improve the contrast and gloss of the images [4]. In this paper, we have presented the comparative analysis of the proposed defogged algorithm and existing visibility restoration algorithms by fog reduction factor (FRF) [5], the measure of enhancement factor (EMF) [6] and a blind parameter η [37].

The structure of this research paper is as follows: Section 2 gives related work regarding visibility restoration algorithms. Section 3 presents proposed defogged algorithm for visibility and contrast enhancement of foggy color images. In section 4 describe the results and discussion. Finally, draw a conclusion of this paper in section 5.

2. Related work

Many algorithms have been proposed during the previous years by the researchers in visibility enhancement and restoration of real world images for various vision based applications. In [2], Tarel et al. presented a fast algorithm for visibility restoration of images degraded by different weather conditions. This algorithm is fastest among other existing visibility restoration algorithms, but the complexity of visibility restoration function is it's linearly dependency on the number of image pixels. In [2], First-time a median filter based visibility restoration technique is applied for visibility enhancement of foggy or hazy images. This algorithm is applied for various applications such as the sign, lane-marking, and obstacle detection, etc. In [3], Choudhury et al. described a trilateral filter concept for edge preserving and smoothing in high gradient region of the image. Author also explains the advantage of trilateral filter over bilateral filter. In [4], Gu et al. describe a histogram modification framework through S-shape transfer mapping function for improving the brightness and contrast of the images. In [5], Choi et al. proposed a dubbed density of fog assessment based defogger (DEFADE) model to remove haze from weather degraded image. The DEFADE algorithm is a kind of statistics of outdoor haze-free

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images. It is based on Fog Aware density Evaluator (FADE), a key observation for reference less perceptual image defogging. By this observation, one can directly estimate the thickness of the haze and obtain a haze-free image. The drawback of this DEFADE algorithm was that it required all statistical features define the perceptual fog density. In [7], He et al. proposed dark channel prior, to remove the haze from a single input image. Using the concept of dark channel prior, author estimated the thickness of the haze directly and recovers a good quality haze-free image. This model failed due to constraint air light assumption that is very influential. In [8], He et al. proposed a guided filter for edge preserving and smoothing in computer vision and computer graphics applications. In [9], Caraffa et al. proposed a guided bilateral filter, for edge-preserving and smoothing for degraded images in many applications. It can also handle the non-Gaussian noise in the image, so this guided bilateral filter is also used for depth map refinement and fog removal in foggy images. In [10], Ancuti et al. proposed a fusion technique based on two hazy images input by applying a white balance and contrast enhancing procedure. This fusion based technique is act also for a single haze image approach for enhancement of visibility in real time application. The main problem of this algorithm is to work effectively only by choosing appropriate weight maps for obtaining the effective de-haze images. In [11], Meng et al. proposed a constrained with a weighted L_1 norm based model to estimate the scene transmission for hazy images but this method is computationally complex, hence it cannot be applied for real time applications. In [12], Li et al. focused on de-hazing of night time images. In this paper, authors added a glow term in hazy model proposed by Koschmieder [13]. By reducing the effect of glow, the night time image treated with direct transmission and air light only. Here the problem in the algorithm is that author takes a rough approximation for atmospheric Light and assumes it is locally constant. In [13], Tarel et al. proposed a local algorithm for the speed and possibility to handle color and gray-scale images. The Algorithm has small number of parameters. In this paper, authors generated several types of synthetic fog through camera images and rating the visibility restoration algorithms by a new scheme. Author also presented a Comparative study and quantitative evaluation with other existing visibility restoration algorithms. In this paper, authors demonstrated that the proposed defogged algorithm produced better results with homogeneous fog as well as the heterogeneous fog. Metrics were used in this algorithm to compute the depth map of restored image by focusing on the road scene only. In [14], Zhu et al. proposed a mathematical model to obtained scene depth estimation of the foggy images. In this work, authors estimate depth map of the foggy image with the help of linear mathematical model, and then estimate the transmission. After estimating the transmission, it restores the scene radiance through the atmospheric scattering model and finally, enhances the foggy images. Existing model has a constant scattering assumption throughout single image de-hazing algorithm.

In [15], Narasimhan et al. analyzed the visual manifestations of different weather conditions and described two important fundamental scattering models and developed technique to estimate the scene properties, and scene structure for the images taken under foggy and other bad weather condition. In [16], Narasimhan et al. described the mathematical model for scenes appearances in homogeneous bad weather conditions. Author derived the intensity changing scene points in the foggy image for detecting the depth discontinuities in computing scene structure under different weather conditions. Finally, apply a fast algorithm to restore the contrast presented in the scene. Entire analysis observed for monochrome image only. In [17], Nicolas et al. proposed a method for improving the enhancement of hazy images. In this paper, authors described the fog region of interest for better segmentation, after that computed the fog density for the position of the horizon line. Limitation of the method is that, the road is flat and a segmentation of the connected component is provided free space in front of the vehicle. In [18], Tan proposed a method that is based on two basic observations. In first observation, images with clear day image have more contrast than hazy or foggy images degraded by bad weather, and second observation is air light whose variation mainly depends on the distance of objects to the viewer. Therefore, relying on these two observations, authors have proposed a cost function in the framework of Markov random fields. Hence, it can be efficiently optimized by different optimization algorithms such as graph-cuts or belief propagation methods. The main drawback of this model is that, some halo effect present in the observed images.

In [19], Li et al. proposed the algorithm for contrast enhancement and tone curve manipulations for the JPEG images which are degraded by haze, fog or some other means. In [20], Lee et al. presented a detailed review on dark channel prior based image de-hazing algorithms. In this paper, author's mainly described the removal of haze under the physical degradation model. Authors focused on mainly four steps: atmospheric light estimation, transmission map estimation, transmission map refinement, and image reconstruction. This four-step de-hazing process makes it possible to provide a step-by-step approach to the complex solution of the visibility enhancement problems. In [21], Ren & Liu developed a multi-scale deep neural network for single image de-hazing. In this paper, authors created a transmission map for corresponding hazy image and refine the result locally but this method is computationally complex, hence it cannot be applied for real time applications. In [22], Hussain et al. proposed a novel approach for camera-based advanced driver assistance systems using deep neural network. In this paper, authors have used a deep neural network for mathematically modelling of fog in an image. But the authors have not evaluated quantitative performance metrics such as fog density.

In [23], Huang et al. analyzed the haze formation with the help of Laplacian distribution model, chromatic adaptive parameter and gamma correction approach. In this paper, authors proposed the adaptive parameters for the visibility restoration of sand storm images, which comes under thick haze formation. In [24], Li et al. proposed a content dark channel prior for the visibility enhancement of foggy images. In conventional dark channel prior, the images suffered from over saturation and artefacts like the halo effect. So author used content dark channel prior to restore the content of the image and post enhancement technique to preserve the local contrast. In [25], Bag et al. proposed a visibility restoration technique for minimal artefacts in de-hazy images. In this paper, authors have used quad tree decomposition method and entropy based contextual regularization for estimation of airlight in hazy images. In [26], Cheng et al. proposed a Gaussian distribution model for estimation of airlight in hazy image. Airlight is an important parameter in hazy image to calculate the real scene. In previous methods brightest pixel in image assume to be airlight, which is a rough approximation. In [27], Chen et al. described bi-histogram modification techniques for visibility restoration of weather degraded images. Authors estimated and calculated the haze density in hazy images through transmission map and applied a Bi-histogram modification technique for visibility enhancement of hazy images. In [28], Chen et al. proposed a Fisher's linear discriminant based dual dark channel prior method for visibility restoration of hazy images. This technique is helpful in the presence of local light sources and under color shifting problems. In [29], Pal et al. proposed a median filter based visibility restoration technique with automatic color enhancement algorithm for foggy color images. In [30], Pal et al. proposed an algorithm for visibility enhancement of foggy images. Authors used a guided bilateral filter based visibility restoration and contrast enhancement algorithm is applied for visibility enhancement of foggy images. Author compares the proposed defogged algorithm to other existing visibility restoration algorithms in terms of quality matrix like fog reduction factor and visibility of enhancement factor. In [33], Guo et al. proposed a low light image enhancement (LIME) technique through the refining of illumination map via a solver algorithm. This technique is useful for lower visible and dim images. In [34], Cai et al. described a convolution neural network based contrast enhancement technique for preserving the image details. In [35], Chen et al. proposed a contrast enhancement technique for image quality control based entropy preserving mapping prior and the learning parameter of dual objective function solved by turbulent swarm optimization (TPSO) technique but this method is computationally complex.

3. Proposed framework

In this section, we have presented detailed discussion and analysis of proposed framework for the visibility enhancement of weather degraded images, which are suffered from fog or haze, dull in color, rough edges and corners. The proposed framework is described in two phases: in the first phase modified trilateral filter based visibility restoration algorithm is applied for smooth and fog free images. Further, in the second phase, S-shaped transfer mapping is used for contrast enhancement of defogged images. The schematic diagram of proposed defogged algorithm is shown in Fig. 1.

3.1. Modified visibility restoration approach

The image degradation model of foggy images is designed by Koschmieder [13], which is given in Eq. (1):

$$J(x,y) = J_0(x,y)e^{-\beta L(x,y)} + J_s(1 - e^{-\beta L(x,y)}) \tag{1}$$

where $J(x, y)$ is apparent luminance of pixel (x, y) at a distance of $L(x, y)$, $J_0(x, y)$ is intrinsic luminance and J_s is sky luminance value, and β is an extinction coefficient for atmosphere, extinction coefficient depends on the wavelength and particle size present in the atmosphere. For fog, $\beta = 1$, means all the wavelength scattered equally and whitish color appeared in the atmosphere. This gray level model is extended to color images for each R, G, B component separately. Visibility restoration demands the estimation of real color of images $J_0(x, y)$ and other foggy properties like β, J_s and depth

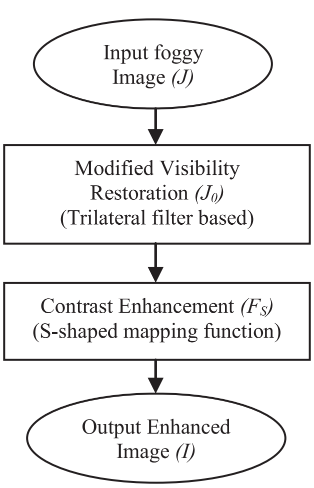

Fig. 1. Block diagram of proposed defogged algorithm.

scene $L(x, y)$. If the scene depth is not known, it is very difficult to separate between β and L as describe in Eq. (1), therefore compute intensity of atmospheric veil is estimated as follows [2]:

$$A(x,y) = J_s(1 - e^{-\beta L(x,y)}) \Rightarrow e^{-\beta L(x,y)} = \left(1 - \frac{A(x,y)}{J_s}\right) \tag{2}$$

Now substitute the value of $e^{-\beta L(x,y)}$ in Eq. (1) and reform this equation as:

$$J(x,y) = J_0(x,y)\left(1 - \frac{A(x,y)}{J_s}\right) + A(x,y) \tag{3}$$

Now let us consider $J(x, y)$ is the observed image intensity for gray-scale or color images at pixel (x, y) and $J_0(x, y)$ is the defogged image intensity. The defogged image intensity is derived from Eq. (4)

$$J_0(x,y) = \frac{J(x,y) - A(x,y)}{\left(1 - \frac{A(x,y)}{J_s}\right)} \tag{4}$$

J_s assume to be the brightest pixel in the opaque region of the image [7]. For visibility restoration of images, the analysis of atmospheric veil or airlight $A(x, y)$, First assumption is that when observed foggy image is known, means $A(x, y) \geq 0$ and pure white, it does not exceed from minimum of $J(x, y)$. To compute image, take some assumption, $T(x, y) = minimum\ of\ J(x, y)$ for each pixel in RGB, where $T(x, y)$ is a foggy image in the observed image $J(x ,y)$, for gray scale image $T(x, y) = J(x, y)$ and for coloured image process R, G, B component separately. In second assumption $A(x, y) \leq T(x, y)$ the problem is formalized as optimized the maximum of $A(x,y)$ [2].To perform edge preserving and smoothing, we have used trilateral filter (*Trilf*) [3]. The intensity of atmospheric veil is obtained by Eq. (7).

$$U(x,y) = \underset{p_v}{Trilf}\,(T(x,y)) \tag{5}$$

$$V(x,y) = U(x,y) - \underset{p_v}{Trilf}\,(|T(x,y) - U(x,y)|) \tag{6}$$

$$A(x,y) = \max(\min(nV(x,y), T(x,y)), 0) \tag{7}$$

where p_v is the size of disc window. n is control parameter for visibility strength, where $n = [0, 1]$. In this algorithm take n = 0.9 and p_v = 64, these both parameter control the visibility restoration.

In Fig. 2 shows that by using trilateral filter, the irregular part is diminished and natural smooth shape of the object is clearly visible. Trilateral filter is the better approximation of the scene illumination with sharp and smooth signal with local constant gradient. It is the combined form of two modified bilateral filter stage. In a trilateral filter, the contribution of two bilateral filters are (i) the filter window is tilted by angle θ to provide the sharp changes in high gradients and outliers cover the filter window through the gradient vector G_θ as shown in Fig. 2. (ii) Adaptive region growing through similar smoothed gradient values solved by one set of parameter [3]. The tilting vector G_θ around the input image point $T(x)$ is

$$G_\theta(x) = \frac{1}{K_\theta(x)} \int_{-\infty}^{\infty} \nabla T(x + \psi) c(\psi)\ s(\|\ \nabla T(x+\psi) - \nabla T(x)\ \|)\ \ d\psi \tag{8}$$

$$K_\theta(x) = \int_{-\infty}^{\infty} c(\psi) s(\|\ \nabla T(x+\psi) - \nabla T(x)\ \|)\ d\psi$$

Whereas the output of Trilateral filter is optimized as [3]:

$$U(x) = \frac{1}{K(x)} \int_{-\infty}^{\infty} T(x+\psi) w(\psi) d\psi \tag{9}$$

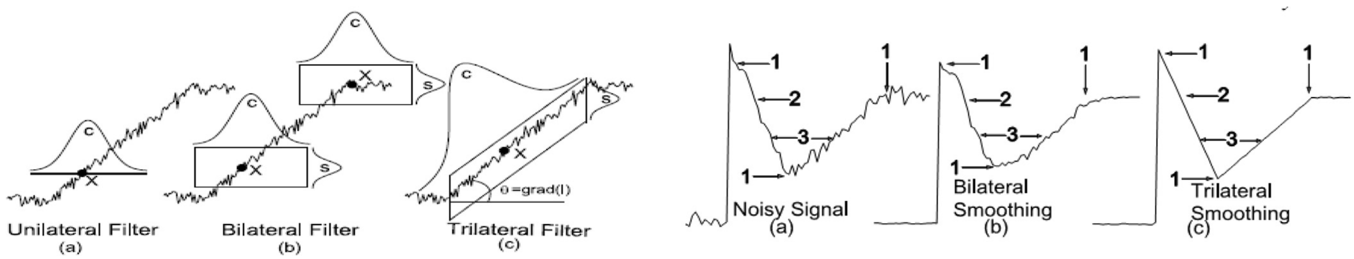

Fig. 2. Functioning and Smoothing output of trilateral filter in comparison to bilateral filtering [3].

where $T(x+\psi)$ is the input of image signal and ψ is the offset vector for measuring position of local neighbourhood of pixel x.

$$w(\psi) = (1 - a(x))c(\psi) + a(x)c(\psi).s(T(x+\psi) - T(x)) \int_{-\infty}^{\infty} d\psi \quad (10)$$

Where $\nabla$is forward difference operator, $c(.)$ and $s(.)$ functions denote the domain (geometric) and range (photometric) similarity between point x and ψ, as that in the bilateral filter, $a(x)$ is regularized local signal at pixel x, $K(x)$ is a normalized factor for dc component of low pass signals.

3.2. S-shape transfer function

After applying modified visibility restoration approach, we applied S-shaped transfer mapping function for contrast enhancement of the dull defogged images. For input defogged images J_0, the S-shaped transfer mapping function $F_s(.)$ for contrast enhanced image I is [4]:

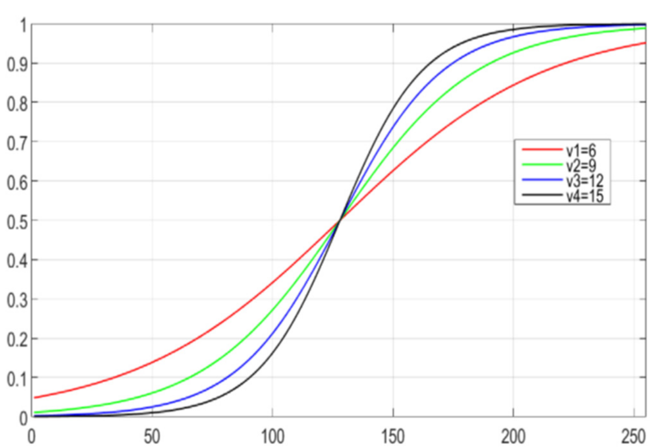

Fig. 3. S-shaped mapping function with slope control parameter v_4.

$$I = F_s(J_0, \xi) = \frac{\xi_1 - \xi_2}{1 + e^{(-(J_0 - \xi_3)/\xi_4)}} + \xi_2 \quad (11)$$

Parameter ξ contains four free parameter ξ_1, ξ_2, ξ_3, ξ_4 to be solved. We assume that transfer curve contained the points (u_i, v_i), $1 \le i \le 4$. for curve symmetry for central brightness set the value of points, $(u_1, v_1) = (0, 0)$, $(u_2, v_2) = (P_{max}/2, P_{max}/2)$, where P_{max} is maximum intensity level, for 8 bit image $P_{max} = 255$, $(u_3, v_3) = (P_{max}, P_{max})$, $u_4 = 25$ and v_4 is control parameter to alter the curvature of S-function, Here we take $v_4 = 15$ for symmetrical S shape function.The symmetrical S shape function and central contrast level are shown in Fig. 3.

$$\xi_{opt} = \arg\min_{\xi} \sum_{i=1}^{4} |v_i - F_s(u_i, \xi)| \quad (12)$$

After obtaining ξ_{opt} , image J_0 enhanced as:

$$I = \max\{\min[F_s(J_0, \xi_{opt}), 255], 0\} \quad (13)$$

Where min and max operation bound the pixel value within 0–255.

3.3. Illustration of proposed algorithm

This subsection illustrates the effect of visibility enhancement in each step for the proposed algorithm. It demonstrates the effectiveness of combining improvement of trilateral filter based visibility restoration and contrast enhancement by S-shape mapping function for defogged of color foggy images, it enhances minute details present in the color foggy images with less artefacts. Quantitative results of each stage have been evaluated using the image quality metrics like Fog Reduction factor *(FRF)*, measure of enhancement (*EME*), measure of enhancement factor (*EMF*) and blind image parameter η for image 1 (aerial.bmp) and image 2 (y11_photo.png), which are given in Table 1 and there definition and mathematical expression are given in the section 4. Best image quality metrics in Table 1 is represented by bold letter. From the Table 1 and visual result of image 1 and image 2 in Fig. 4, it is clear that proposed defogged algorithm provides better quantitative and qualitative results as compared to trilateral filter based visibility

Table 1
Quantitative performance comparison of each modification of proposed algorithm for two foggy images.

Quality parameter	Image 1 (aerial.bmp)			Image 2 (y11_photo.png)		
	Trilateral filter based visibility restoration	Contrast enhancement by S-shape mapping Function	Proposed defogged Algorithm	Trilateral filter based visibility restoration	Contrast enhancemen by S-shape mapping Function	Proposed defogged Algorithm
D_f of foggy Image (input)	3.1911	3.1911	3.1911	3.5984	3.5984	3.5984
D_{df} of defogged image (processed)	1.6088	2.1073	1.3423	2.1502	1.8676	1.3210
FRF value	1.5823	1.0838	**1.8488**	1.4482	1.7307	**2.2774**
EME of foggy image (input)	8.4791	8.4791	8.4791	7.6244	7.6244	7.6244
EME of defogged image (processed)	28.3590	11.8069	30.4745	14.3677	11.0662	16.5307
EMF value	3.3445	1.3925	**3.5941**	1.8844	1.4514	**2.1681**
η value	2.7411	2.1969	**2.8478**	3.3397	2.6808	**4.1341**

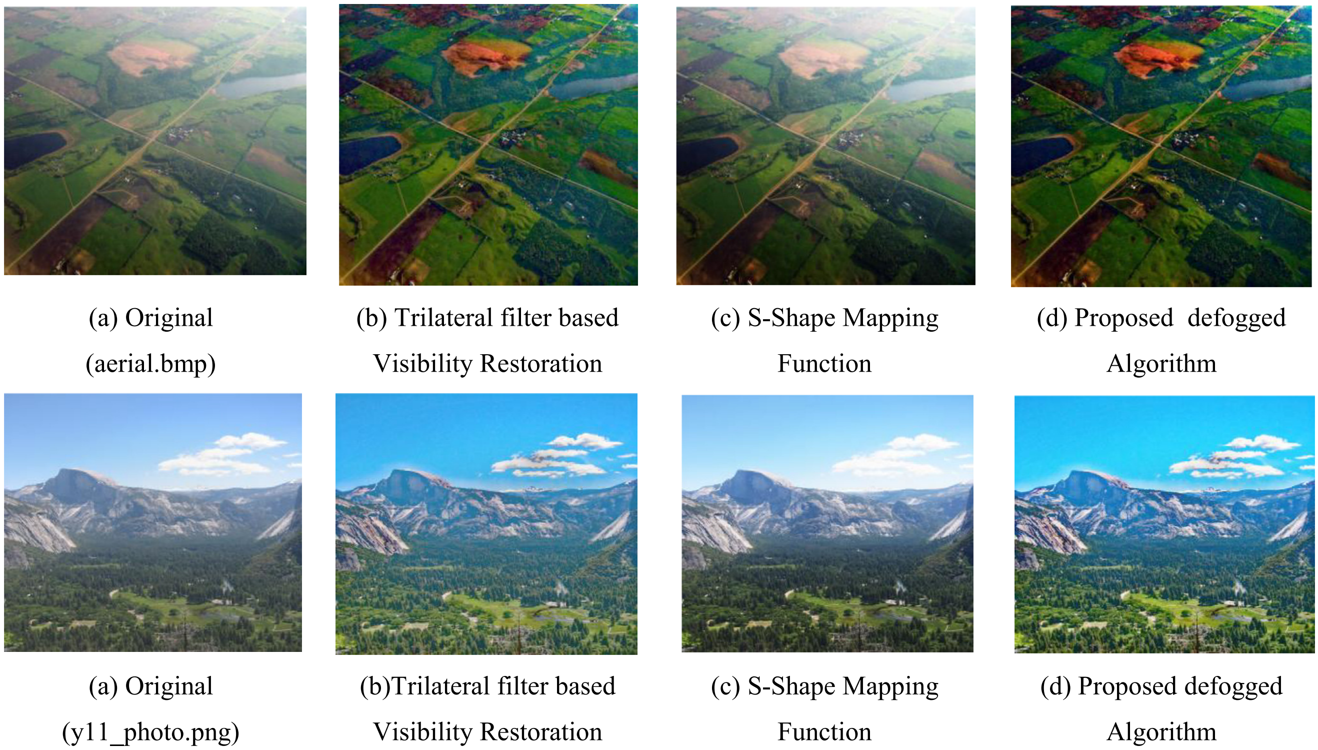

Fig. 4. Visibility Enhancement steps for foggy images under (a) original image (b) Trilateral filter based visibility restoration method (c) Contrast enhancement by S-shape mapping function (d) Proposed algorithm.

restoration approach and contrast enhancement by S-shape mapping function.

4. Results and discussion

In this section, we have presented quantitative and qualitative performances of the simulation results of proposed defogged algorithm and other existing visibility restoration algorithms on different foggy image databases. To compute results of proposed defogged algorithm and other recent existing visibility restoration algorithms are implemented on a 64-bit system with Core i3 processor with 4 GB RAM and MATLAB [release 2015a] software.

4.1. Image database

The simulation results of proposed defogged algorithm and other recent existing visibility restoration algorithms are obtained on different test foggy images which are taken from the Tarel et al. foggy image database [2] @ http://perso.lcpc.fr/tarel.jean-philippe and Lark Kwon Choi et al. foggy image database [5] @ http://live.ece.utexas.edu/research/fog/index.html. The names of the images are same in the database.

4.2. Quality performances metrics

In order to evaluate the performance parameters of proposed defogged algorithm, we have tested proposed defogged algorithm and recent existing visibility restoration algorithms on different standard test foggy images [2,5]. Quality parameters have been evaluated on 100 test images from the database but we have presented visual results of only seven different format foggy images [i.e. y11_photo.png (512X512), cones.jpg (512X512), pumpkin.jpg (512X512), dooars02.jpg (512X512), Tiananmen1.png (512X512), forest.bmp (512X512), aerial.bmp (512X512)] from database [2,5]. The first parameter, prediction of perceptual fog density (D) is calculated in the foggy image as well as corresponding defogged image. Fog aware density evaluator (FADE) is used for calculating the fog in a image [5]. It is based on natural scene statistics like local mean, Local coefficient of variance for sharpness, contrast energy, Image entropy, pixel-wise dark channel prior, colour saturation and colourfulness matrix [5]. To find the fog density, there are twelve feature calculated in a square nxn image. The numerical value of FRF is defined the difference between the fog densities of input colour foggy image (D_f) to output defogged colour image (D_{df}). After calculating fog density of foggy image and Defogged image, we can calculate fog reduction factor (FRF), which is defined as in Eq. (14):

$$FRF = D_f - D_{df} \tag{14}$$

where D_f is the fog density in the input foggy image and D_{df} is the fog density in the output defogged image. Higher the value of Fog reduction factor better is the visibility restoration algorithm.

The second image quality parameters, we use to judge the performance of proposed defogged algorithm are measure of enhancement (EME) and measure of enhancement factor (EMF) [6,31,32]. These are the arbitrary choice for the researchers to judge the quality of color defogged images. So, the value of EMF and EME provide the visual quality of the obtained image. So the better value of EME and EMF gives the quality of the algorithm. The performance of proposed defogged algorithm and other existing visibility restoration algorithms such as Tarel et al. [2], Zhu et al. [14], Ancuti & Ancuti [10], He et al. [8], Meng et al. [11], Li et al. [12], Choi et al. [5] and Ren et al. [21] are compared in terms of EME and EMF.

The EME and EMF image quality metrics of proposed algorithm and others existing visibility restoration algorithms are evaluated and given in Tables 2–6 respectively. The measure of enhancement (EME) for image $I(x,y)$ of a dimensions $N_1 \times N_2$ pixels is given as follows:

Table 2
Performance comparison of various visibility enhancement algorithms for foggy image (y11_photo.png, 512X512).

Algorithm	D_f of foggy image	D_{df} of Defogged image	FRF value	EME of foggy image	EME of Defogged image	EMF value
Tarel et al.	3.5984	2.4315	1.1669	7.6244	11.4169	1.4974
Zhu et al.	3.5984	1.6442	1.9542	7.6244	11.6437	1.5272
Ancuti & Ancuti	3.5984	1.6070	1.9914	7.6244	11.2399	1.4743
He et al.	3.5984	3.0972	0.5012	7.6244	13.6476	1.7900
Meng et al.	3.5984	1.8793	1.7191	7.6244	15.3592	2.0145
Li et al.	3.5984	1.4216	2.1768	7.6244	16.3154	2.1399
Choi et al.	3.5984	1.4638	2.1346	7.6244	10.2818	1.3485
Ren et al.	3.5984	1.4392	2.1592	7.6244	15.4389	2.0249
Proposed defogged algorithm	**3.5984**	**1.3210**	**2.2774**	**7.6244**	**16.5307**	**2.1681**

Table 3
Performance comparison of various visibility restoration algorithms for foggy image (cones.jpg, 512X512).

Algorithm	D_f of foggy image	D_{df} of Defogged image	FRF value	EME of foggy image	EME of Defogged image	EMF value
Tarel et al.	3.7757	2.3486	1.4271	8.7478	16.3636	1.8706
Zhu et al.	3.7757	2.1989	1.5768	8.7478	0.9547	1.2523
Ancuti & Ancuti	3.7757	2.1207	1.6550	8.7478	14.3092	1.6357
He et al.	3.7757	3.1277	0.6480	8.7478	18.9639	2.1678
Meng et al.	3.7757	1.6580	2.1177	8.7478	19.0601	2.1788
Li et al.	3.7757	1.4690	2.3067	8.7478	15.6770	1.7921
Choi et al.	3.7757	1.6971	2.0786	8.7478	20.4249	2.3348
Ren et al.	3.7757	1.7360	2.0397	8.7478	18.4471	2.1088
Proposed defogged algorithm	**3.7757**	**1.3222**	**2.4535**	**8.7478**	**24.3535**	**2.7839**

Table 4
Performance comparison of various visibility enhancement algorithms for foggy image (pumpkin.jpg, 512X512).

Algorithm	D_f of foggy image	D_{df} of Defogged image	FRF value	EME of foggy image	EME of Defogged image	EMF value
Tarel et al.	3.0866	1.9231	1.1635	11.2031	21.3600	1.9066
Zhu et al.	3.0866	1.9285	1.1581	11.2031	13.2689	1.1844
Ancuti & Ancuti	3.0866	1.7820	1.3047	11.2031	16.1149	1.4384
He et al.	3.0866	2.6843	0.4023	11.2031	16.9160	1.5099
Meng et al.	3.0866	1.6112	1.4754	11.2031	20.3385	1.8154
Li et al.	3.0866	1.3457	1.7409	11.2031	16.7592	1.4959
Choi et al.	3.0866	1.5897	1.4969	11.2031	13.3582	1.1924
Ren et al.	3.0866	1.3197	1.7669	11.2031	21.4429	1.9140
Proposed defogged algorithm	**3.0866**	**1.2221**	**1.8645**	**11.2031**	**29.6520**	**2.6468**

Table 5
Performance comparison of various visibility enhancement algorithms for foggy image (dooars02.jpg, 512X512).

Algorithm	D_f of foggy image	D_{df} of Defogged image	FRF value	EME of foggy image	EME of Defogged image	EMF value
Tarel et al.	3.5553	2.4208	1.1345	11.0610	19.0696	1.7240
Zhu et al.	3.5553	2.0731	1.4821	11.0610	14.8591	1.3434
Ancuti & Ancuti	3.5553	2.0108	1.5445	11.0610	16.8726	1.5254
He et al.	3.5553	3.0908	0.4645	11.0610	19.3773	1.7519
Meng et al.	3.5553	1.4938	2.0615	11.0610	25.8238	2.3347
Li et al.	3.5553	1.3200	2.2353	11.0610	24.5400	2.2186
Choi et al.	3.5553	1.8947	1.6605	11.0610	24.8585	2.2474
Ren et al.	3.5553	1.6560	1.8992	11.0610	20.8752	1.8873
Proposed defogged algorithm	**3.5553**	**1.3131**	**2.2422**	**11.0610**	**27.6323**	**2.4982**

Table 6
Performance comparison of various visibility enhancement algorithms for foggy image (Tiananmen1.png, 512X512).

Algorithm	D_f of foggy image	D_{df} of Defogged image	FRF value	EMEof foggy image	EME of Defogged image	EMF value
Tarel et al.	3.4643	1.5983	1.8659	4.9741	14.0334	2.8213
Zhu et al.	3.4643	2.0654	1.3989	4.9741	6.1376	1.2339
Ancuti & Ancuti	3.4643	1.8476	1.6167	4.9741	7.8267	1.5735
He et al.	3.4643	2.9420	0.5223	4.9741	9.6313	1.9363
Meng et al.	3.4643	1.7933	1.6710	4.9741	11.1601	2.2436
Li et al.	3.4643	1.3503	2.1140	4.9741	8.6521	1.7394
Choi et al.	3.4643	1.3281	2.1362	4.9741	7.6730	1.5426
Ren et al.	3.4643	1.5526	1.9116	4.9741	9.7856	1.9673
Proposed defogged algorithm	3.4643	**1.2031**	**2.2611**	4.9741	**16.8765**	**3.3939**

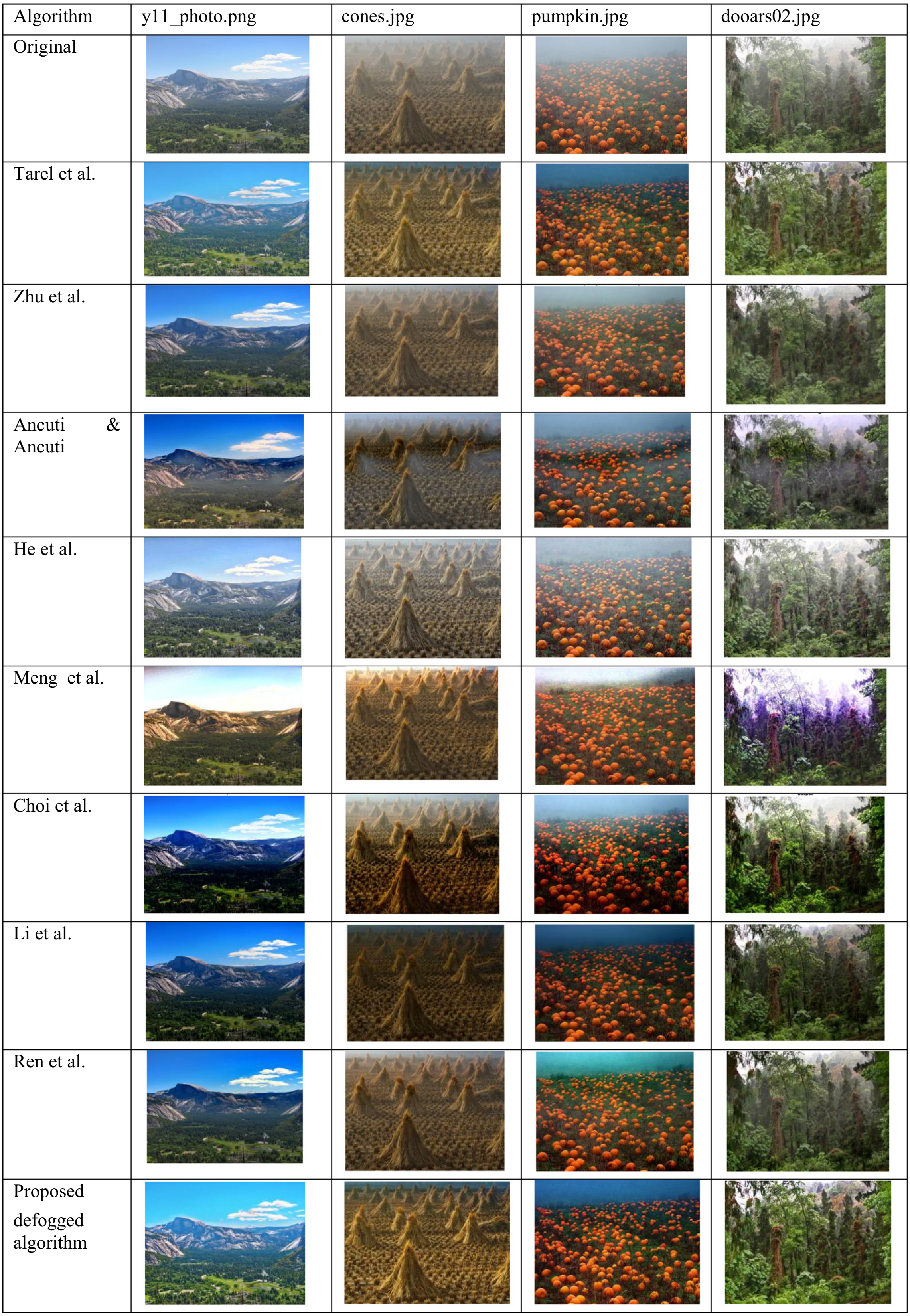

Fig. 5. Defogged result of different images (512X512) for various visibility restoration algorithms.

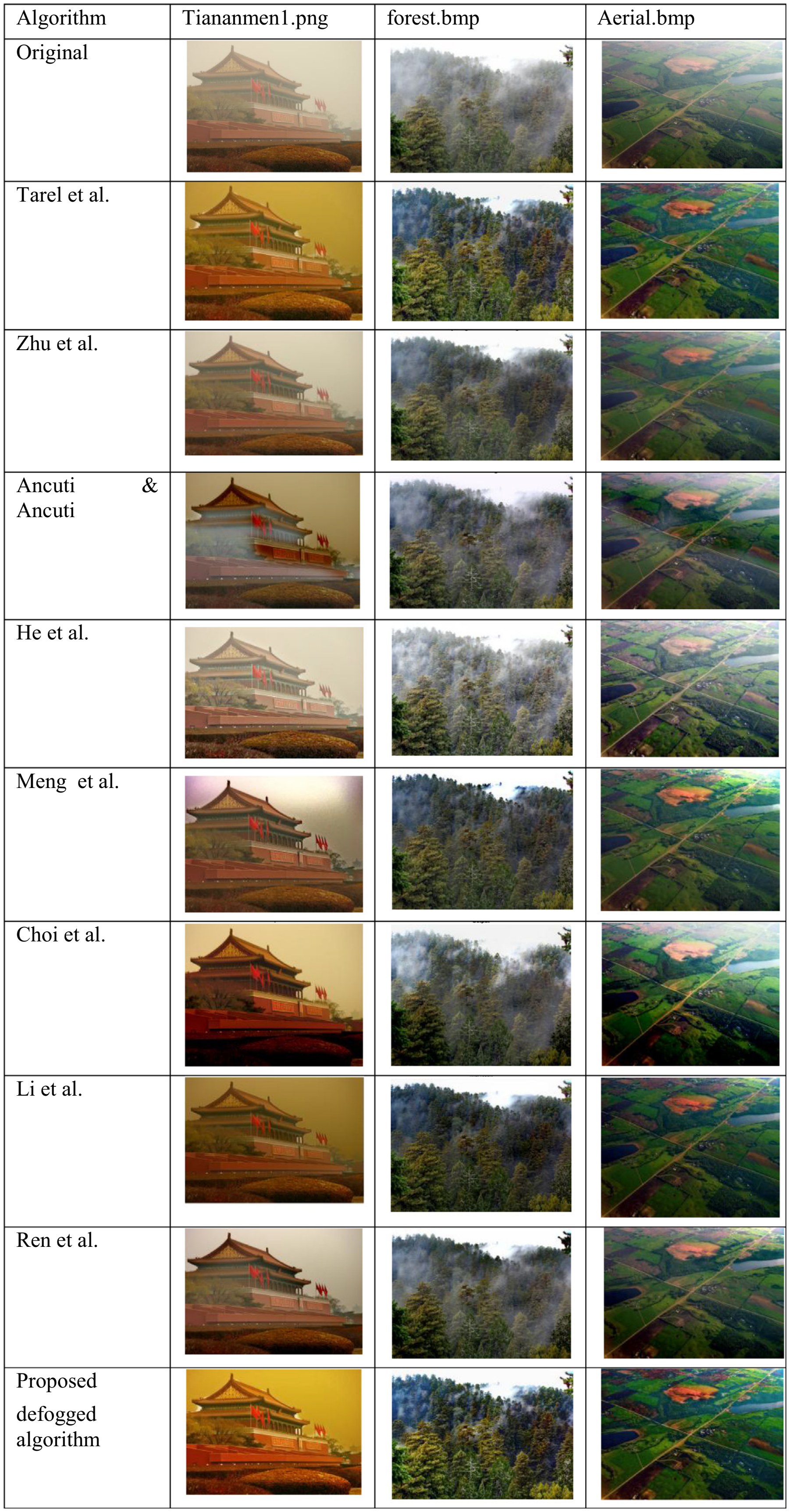

Fig. 6. Defogged result of different images (512X512) for various visibility restoration algorithms.

$$EME_{l_1,l_2} = \frac{1}{l_1 l_2} \sum_{1}^{l_1} \sum_{1}^{l_2} \left[20 * \ln\left(\frac{I_{\max}(x,y)}{I_{\min}(x,y)} \right) \right] \quad (15)$$

where an image *(I)* is divided into $l_1 \times l_2$ blocks, $I_{max}(x,y)$ and $I_{min}(x,y)$ are the maximum and minimum pixels value in each block. The measure of enhancement factor (EMF) between output image and input image is defined as [31,32,36]:

$$EMF = \frac{EME_{output\ \ image\ \ ,I(x,y)}}{EME_{input\ \ image\ \ ,J(x,y)}} \quad (16)$$

Further, one more quality parameter is used for the analysis of the proposed defogged algorithm and other existing defogged algorithms. This blind parameter (η) is used to indicate the enhancement degree of the image gradient [37,38]. The parameter η provides the degree of restoration in terms of image edges and texture information. Higher value of η means better defogged algorithm for edge preservation [38].

$$\eta = \exp\left[\frac{1}{n_r} \sum_{i \in S_r} \log \eta_i \right] \quad (17)$$

where n_r is the cardinal numbers of the set of visible edges in output defogged image and$\eta_i = \frac{\Delta I_r}{\Delta J_i}$, ΔJ_i and ΔI_r are the gradients of the original foggy image and corresponding defogged image. S_r is the set of visible edges in restored image.

4.3. Discussions

The performance of proposed defogged algorithm and other existing visibility restoration algorithms were tested on different foggy color images from the different image database [2,5], but here we have shown here only results of seven standard foggy images and average quantitative value of hundred foggy images. We have applied different existing visibility restoration algorithms like Tarel et al. [2], Zhu et al. [14], Ancuti & Ancuti [10], He et al. [8], Meng et al. [11], Li et al. [12], Choi et al. [5] and Ren et al. [21] algorithms on these foggy images. Performance of proposed defogged algorithm and other existing visibility restoration algorithms were compared in terms of perceptual fog density (D) and Fog reduction factor (FRF). We have calculated of fog density (D) and Fog reduction factor (FRF) values for different visibility restoration algorithms for images in Figs. 5 and 6. Its numerical values are given in Tables 2–6. We have also shows the average value of FRF on hundred foggy images for proposed and different existing visibility restoration algorithms in Table 9.

Here, we observed from Tables 2–9 that, the proposed defogged algorithm has better value of FRF in comparison to corresponding all other existing visibility restoration algorithm. It means proposed defogged algorithm provided better defogged images in comparison with other existing visibility restoration algorithms such as Tarel et al. [2], Zhu et al. [14], Ancuti & Ancuti [10], He et al. [8], Meng et al. [11], Li et al. [12], Choi et al. [5] and Ren et al. [21] algorithms. Second image quality parameters were measured in terms of measure of enhancement (EME) and measure of enhancement factor (EMF). We have also calculated the EME and EMF value for all existing and proposed defogged algorithm for images given in Fig. 5, Fig. 6 and average value of the EMF on hundred foggy images including PNG, BMP and JPEG images. It's corresponding numerical values were given in Tables 2–9. Here, we observed from Tables 2–9 that the proposed defogged algorithm provides better EMF value in comparison with other existing visibility restoration algorithms. The third parameter η is a blind parameter. It is used to analysis the performance of proposed defogged algorithm and other existing defogged algorithms. The

Table 9
Average Performance comparison of various visibility enhancement algorithms for 100 foggy images (.png, .bmp and .jpg images).

Algorithm	FRF	EMF	η
Tarel et al.	1.5377	2.3513	3.1402
Zhu et al.	2.0246	2.4830	2.6390
Ancuti & Ancuti	2.1857	2.4479	2.4138
He et al.	2.2394	2.2859	3.3542
Meng et al.	1.9278	2.1063	3.0814
Li et al.	2.4134	1.8280	2.1496
Choi et al.	2.4527	2.8357	2.4834
Ren et al.	2.3350	2.0283	2.5718
Proposed defogged algorithm	**2.8979**	**3.1892**	**3.5082**

Table 7
Performance comparison of various visibility enhancement algorithms for foggy image (forest.bmp, 512X512).

Algorithm	D_f of foggy image	D_{df} of Defogged image	FRF value	EME of foggy image	EME of Defogged image	EMF value
Tarel et al.	3.5059	2.2689	1.2370	12.4060	28.4539	2.2936
Zhu et al.	3.5059	1.9148	1.5911	12.4060	15.9838	1.2884
Ancuti & Ancuti	3.5059	1.8423	1.6636	12.4060	15.7662	1.2709
He et al.	3.5059	2.8042	0.6216	12.4060	16.8992	1.3622
Meng et al.	3.5059	1.5593	1.9466	12.4060	23.7729	1.9162
Li et al.	3.5059	1.0934	2.4124	12.4060	19.9507	1.6081
Choi et al.	3.5059	1.9344	1.5715	12.4060	11.3136	0.9119
Ren et al.	3.5059	1.4033	2.1026	12.4060	14.9372	1.2040
Proposed defogged algorithm	**3.5059**	**1.0272**	**2.4787**	**12.4060**	**38.0657**	**3.0683**

Table 8
Performance comparison of various visibility enhancement algorithms for foggy image (aerial.bmp, 512X512).

Algorithm	D_f of foggy image	D_{df} of Defogged image	FRF value	EME of foggy image	EME of Defogged image	EMF value
Tarel et al.	3.1911	1.8086	1.3825	8.4791	22.8750	2.6978
Zhu et al.	3.1911	2.1971	0.9940	8.4791	10.3139	1.2164
Ancuti & Ancuti	3.1911	2.0636	1.1276	8.4791	12.7847	1.5078
He et al.	3.1911	2.4725	0.7186	8.4791	15.9257	1.8782
Meng et al.	3.1911	1.8233	1.3678	8.4791	16.7143	1.9712
Li et al.	3.1911	1.3935	1.7976	8.4791	18.3093	2.1593
Choi et al.	3.1911	1.2495	1.9416	8.4791	9.5184	1.1226
Ren et al.	3.1911	1.4342	1.7569	8.4791	14.9759	1.7662
Proposed defogged algorithm	**3.1911**	**1.3423**	**1.8488**	**8.4791**	**30.4745**	**3.5941**

computation value of η for foggy images and corresponding fog free images given in Figs. 5 and 6 under different existing defogged algorithms and proposed algorithms are shown in Table 10. The average value of η for 100 foggy images under proposed defogged algorithm and other existing defogged algorithms are shown in Table 9. Last we have observed the visualization of the output Defogged images from different visibility restoration algorithms. It can be noticed from Figs. 5 and 6, that our proposed defogged algorithm gives better visually pleasing defogged image as compared to other existing visibility restoration algorithms.

4.4. Object visualization of proposed algorithm

The visualization result of proposed defogged algorithm and other visibility restoration algorithms is presented in Figs. 5 and 6. But in this section, we describe few visualization effect of proposed defogged algorithm which is presented in Fig. 7. In Aerial. bmp objects are more visible in the grassland as marked in the circle shown in Fig. 7(a). From Fig. 7(b), we can easily count the pumpkins at far distance in the pumpkin.jpg after applying the proposed algorithm. In Fig. 7(c), edges and boundaries are clearly visible in Tiananmen1.jpg. In this figure, there is some hallo effect visible behind the building but written text and photo in front of building are clear visible. In Fig. 7(d), the visibility is enhanced in the forest after applying the proposed algorithm. The encircle portion of Fig. 7(d) clear shows the visibility of the branches and trees in the forest. Finally, we can observed from Fig. 7, that proposed defogged algorithm provides better visualization results as compare to other visibility restoration algorithms.

As per the discussion of image processing experts at our institute, regarding output of defogged images of different algorithms the mean opinion score (MOS) is presented in Table 11. Hence, finally we can say that under all observation like FRF, EMF and η from Tables 2–10, visualization results in Figs. 5, 6 and 7, and MOS in Table 11 our proposed defogged algorithm provided better visibility and smoothness results as compared to other existing

Table 10
Performance comparison in terms of blind parameter η under various visibility enhancement algorithms.

Images → / ↓ Algorithm	y11_photo.png	cones.jpg	pumpkin.jpg	dooars02.jpg	tiananmen1.png	forest.bmp	aerial.bmp
Tarel et al.	3.1255	2.7300	2.3945	2.6913	4.0631	2.6570	2.9216
Zhu et al.	3.0158	2.4830	2.1564	2.7300	3.5945	2.3205	2.1035
Ancuti & Ancuti	2.7312	2.1355	2.1416	2.2815	3.6369	1.7794	2.5230
He et al.	3.4594	3.0996	2.6347	2.9733	**5.0791**	2.3807	**3.6116**
Meng et al.	3.1779	3.1019	2.5337	2.8366	3.5852	2.4304	2.2106
Li et al.	2.6412	2.2647	2.0080	1.9675	2.9831	1.6991	1.3245
Choi et al.	2.1859	2.5058	2.0278	2.8062	3.2580	1.7091	2.5508
Ren et al.	2.8562	2.4350	2.0086	2.6748	3.6620	2.0635	2.4240
Proposed defogged algorithm	**4.1341**	**3.5864**	**2.6407**	**3.5045**	4.8851	**2.9254**	2.8478

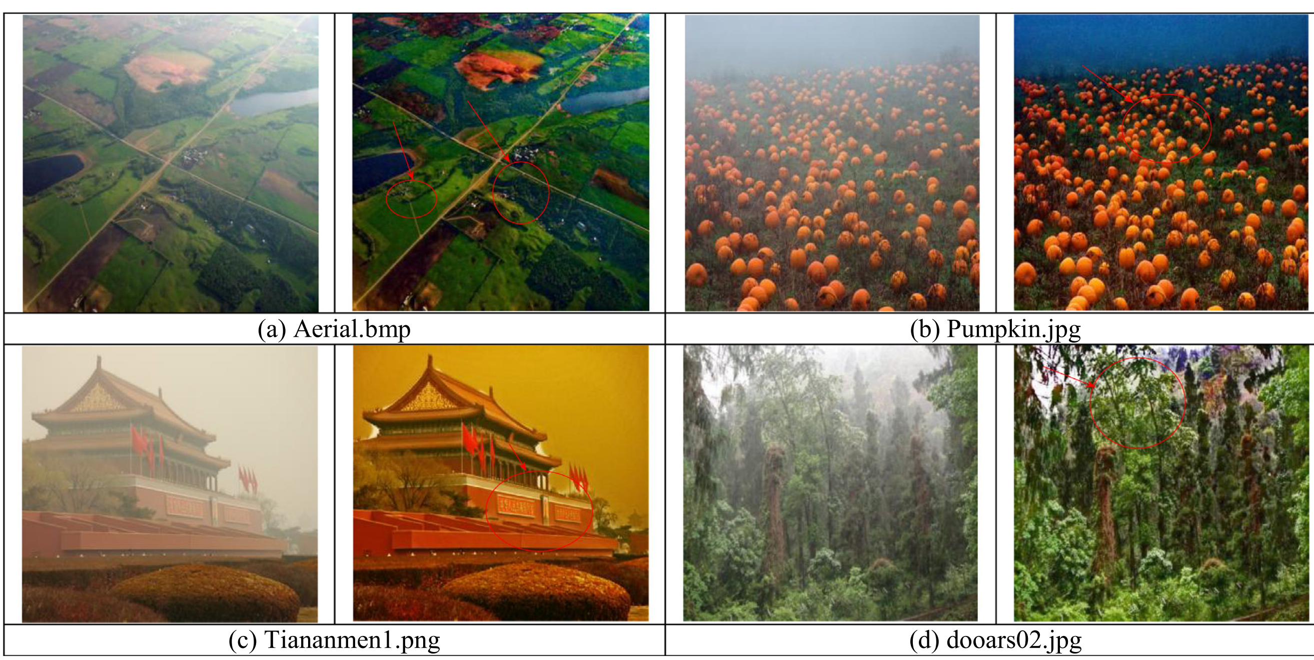

Fig. 7. Visualization of Proposed Algorithm.

Table 11
MOS of different foggy algorithms.

Algorithm	Tarel et al.	Zhu et al.	Ancuti & Ancuti	He et al.	Meng et al.	Choi et al.	Li et al.	Ren et al.	Proposed defogged algorithm
MOS (5)	4.2	4.1	3.7	4	3.8	4.2	4.2	4.3	4.4

visibility restoration algorithms such as Tarel et al. [2], Zhu et al. [14], Ancuti & Ancuti [10], He et al. [8], Meng et al. [11], Li et al. [12], Choi et al. [5] and Ren et al. [21].

5. Conclusion

In this paper, we proposed defogged algorithm for visibility enhancement of color images, which are degraded by foggy weather conditions. In comparison to other existing visibility enhancement algorithms, our proposed defogged algorithm provided visually pleasing defogged images. Proposed defogged algorithm was tested on different foggy color images on different foggy image databases. Quality wise visibility restoration performance of proposed defogged algorithm was evaluated and compared it with other existing visibility restoration algorithms. The performance of proposed defogged algorithm was evaluated in terms of perceptual fog density (D) and Fog reduction factor (FRF) with other existing visibility restoration algorithms. Simulation results indicated that proposed defogged algorithm provided the highest values of FRF in comparison to other existing visibility restoration algorithms. Other parameters which we have evaluated the quality of image in terms of measure of enhancement factor (EMF) and a blind parameter η. Again from the simulation results of a different visibility restoration algorithms on hundred of foggy images demonstrated that, the proposed defogged algorithm provided better results among all algorithms. Visual results were also better as compared to other existing visibility restoration algorithms. Therefore, proposed defogged algorithm performed very effectively and efficiently for visibility restoration of foggy based degraded images. We can also apply proposed defogged algorithm in many other weather degraded images and weather forecasting through satellite images for its clear visibility and smoothness.

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