Mapping and Deep Analysis of Image Dehazing: Coherent Taxonomy, Datasets, Open Challenges, Motivations, and Recommendations

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Abstract

Our study aims to review and analyze the most relevant studies in the image dehazing field. Many aspects have been deemed necessary to provide a broad understanding of various studies that have been examined through surveying the existing literature. These aspects are as follows: datasets that have been used in the literature, challenges that other researchers have faced, motivations, and recommendations for diminishing the obstacles in the reported literature. A systematic protocol is employed to search all relevant articles on image dehazing, with variations in keywords, in addition to searching for evaluation and benchmark studies. The search process is established on three online databases, namely, IEEE Xplore, Web of Science (WOS), and ScienceDirect (SD), from 2008 to 2021. These indices are selected because they are sufficient in terms of coverage. Along with definition of the inclusion and exclusion criteria, we include 152 articles to the final set. A total of 55 out of 152 articles focused on various studies that conducted image dehazing, and 13 out 152 studies covered most of the review papers based on scenarios and general overviews. Finally, most of the included articles centered on the development of image dehazing algorithms based on real-time scenario (84/152) articles. Image dehazing removes unwanted visual effects and is often considered an image enhancement technique, which requires a fully automated algorithm to work under real-time outdoor applications, a reliable evaluation method, and datasets based on different weather conditions. Many relevant studies have been conducted to meet these critical requirements. We conducted objective image quality assessment experimental comparison of various image dehazing algorithms. In conclusions unlike other review papers, our study distinctly reflects different observations on image dehazing areas. We believe that the result of this study can serve as a useful guideline for practitioners who are looking for a comprehensive view on image dehazing.

Keywords

Image Dehazing, Image Defogging, Image Dehazing Algorithms, Evaluation, Image Quality Assessment, Dataset.

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I. Introduction

Computer vision is an interdisciplinary research [1] that is relevant to a wide range of applications that can influence our daily life, such as vehicle navigation, surveillance, and traffic monitoring [2]. Although computer vision applications are popular in indoor environments, they remain constrained in outdoor environments [3]. The degradation of outdoor scene images could be attributed to various reasons, but the main reason is turbid weather. Bad weather conditions could be dynamic (rain and snow) or steady (fog, mist, and haze) depending on the kinds and sizes of particles in the atmosphere and their density in the air [3]. The images capture haze weather are usually degraded in terms of fidelity and low contrast because light is scattered and absorbed as it travels in bad weather conditions. Consequently, most outdoor applications that rely heavily on the quality of input images do not work efficiently because of degraded images [4]. Thus, the enhancement of image quality in bad weather conditions is critical in countless computer vision applications [1].

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Haze is an atmospheric effect that sets a gray color over a scene, thereby decreasing the visibility in outdoor scene images [5]. Haze is also considered one of the main causes of accidents in different environmental mediums, such underwater, air, and land [6]. Particles such as smoke and moisture, which usually spread in the air, scatter the light that propagates through the atmosphere and cause the formation of haze [7]. The process of eliminating haze effects from outdoor images and restoring fidelity details is called dehazing and it is often considered an image enhancement technique [5]. However, it is unlike traditional contrast enhancement methods because the degradation of image pixels induced by the presence of haze depends on the distance between the object and the acquisition device and the regional density of the haze [8].

Fog formation has two aspects, namely, attenuation and airlight. Attenuation reduces contrast, whereas airlight increases whiteness in a scene. In attenuation, the light rays that propagate from a specific scene point due to the scattering of atmospheric particles are attenuated [9]. The light propagating from the source is scattered on its way to the camera and inserts whiteness in the scene or causes color distortion, that is, airlight [10], [11]. Furthermore, the variations of the effects of airlight and attenuation are restricted to the distance between the scene point and the device (e.g., camera). Therefore, the accuracy of the restoration of degraded images mainly depends on the remap concept, that is, the estimation of the depth or airlight map [9].

An image defogging algorithm must be designed to improve the environmental adaptability of visual systems. Many improved defogging algorithms based on physical models have been proposed for use in outdoor scenes [6]. Some video and image defogging algorithms have also been proposed for real-world traffic surveillance scenes [12]. Most existing defogging algorithms are aimed at removing fog from land images. However, few studies on sea and air images exist. In some works, the image defogging algorithm was simply divided into two categories according to whether a physical model was used or not [13]. The first category is image restoration based on a physical model [14], [15], and the other is based on image enhancement [16], [17]. The image restoration method establishes a physical imaging model on the basis of the cause of image degradation under foggy conditions. Under this category, the algorithms must estimate the parameters of the physical model, such as the atmospheric light and transmission (depth) [18]. An image can be restored by inversely solving the physical model. Image restoration algorithms are aimed at obtaining a natural and clear image with good visibility while maintaining good performance in terms of color restoration. The second category of defogging algorithms is based on image enhancement and does not consider the physical imaging model of foggy conditions. Algorithms under this category attempt to use various image enhancement methods to enhance the contrast and visibility of foggy images [6]. In recent years, fusion-based defogging algorithms that enhance images by fusing multiple input images have received considerable attention [19], [20]. Thus, fusion-based defogging algorithms can be regarded as the third category of defogging algorithms. However, image restoration algorithms based on physical models can be divided into two categories according to the number of images used: image restoration based on multiple images [3] and image restoration based on a single image [10], [21] .

To prove the efficiency of a particular algorithm, evaluation and benchmarking are necessary steps in image dehazing. Image quality assessment methods enable us to compare the performance of different image dehazing algorithms. Various foggy scenes have been made available to test the usefulness of image dehazing algorithms [22], [23]. Most forms of assessment are equivalent on several foggy scenes [6], [8], [24], [25]. For example, in [6] the authors considered a variety of evaluation scenes, including inhomogeneous, homogeneous, and dark foggy scenes to test the efficiency of algorithms. Therefore, the advantages and demerits of each algorithm should be considered within each context. Under different hazy scenes, several algorithms can work properly, such as those proposed in [31], [33]. Therefore, comparing these algorithms from only one perspective is unfair [34]. The efficiency of image dehazing algorithms also needs to be evaluated by using trustworthy approaches [24], [37]. In this case, how several algorithms can be evaluated and how the best algorithm is selected through an effective approach warrant further investigation. Different image quality assessment methods have been proposed for evaluation and benchmarking of image dehazing algorithms. So far, there are no reliable means to measure the quality of the image dehazing algorithms [24], [37].

Our study attempts to highlight several aspects within the image dehazing area, and the study contributions can be summarized as follows:

- We highlight the developments in real-time image dehazing algorithms.
- We sum up significant achievements by other researchers in response to image dehazing needs.
- We draw attention to evaluation methodologies and datasets.
- A comprehensive evaluation of experiments is presented based on different algorithms as well as different foggy scenes.
- We propose a taxonomy that maps the existing literature in a well-ordered body and defines various research lines in the image dehazing field. We believe that the outcomes are beneficial to other researchers.

The presents study has been organized into different sections. Section II introduces the details of the systematic review procedure. Section III provides results of the adopted systematic review protocol. Section IV focuses on technical aspects where different reviewed works have been implemented and evaluated based on well-known metrics. Section V discusses with details all achieved results from the proposed taxonomy as well as the evaluation experiments. Section VI highlights the constraints of the present review study. Section VII concludes on the contributions of this study and maps the addressed challenges with achieved outcomes.

II. Systematic Review Protocol

A. Information Sources

In terms of systematic search, we selected three of the most popular online search engine databases: Web of Science (WOS), ScienceDirect (SD), and IEEE Xplore Digital Library. The selection was established according to the index that eases and formulates a simple and complex search query and especially monitors numerous journals and conference papers in the sciences, including computer science and social science. This selection was aimed at including as much literature as possible that covers the maximum number of articles related to image dehazing and technical ones. It was also aimed at providing a holistic view of researchers' achievements in a broad but pertinent variety of disciplines.

B. Study Selection

The study selection technique implied an exhaustive search of related articles involving two steps. First, irrelevant and duplicated articles were excluded by means of scanning the titles and abstract. Second, the articles scanned in the previous step were filtered through full text reading. The same eligibility criteria were applied to the two stages.

C. Search

The article search process was launched on 08 March 2018, and the search query was used on the IEEE, WOS, and SD databases via their search boxes. In all the mentioned databases, searching was carried out using keywords related to terminologies ("image dehazing" OR "image defogging" OR "image dehaze" OR "image defog" OR "hazy image" OR "foggy image" OR "video dehazing" OR "video defogging" OR "haze removal" OR "fog removal") that were combined later through the "AND" operator with the following keywords ("Evaluation" OR "Benchmarking" OR "Assessment" OR "Measurement"), as shown in Fig. 1. Advanced search preferences in each engine were utilized to exclude the chapters of books and other types of documents and to include only the relevant journals and conference papers. Furthermore, we considered the studies that were most undoubtedly immersed in the latest and suitable scientific research related to our study.

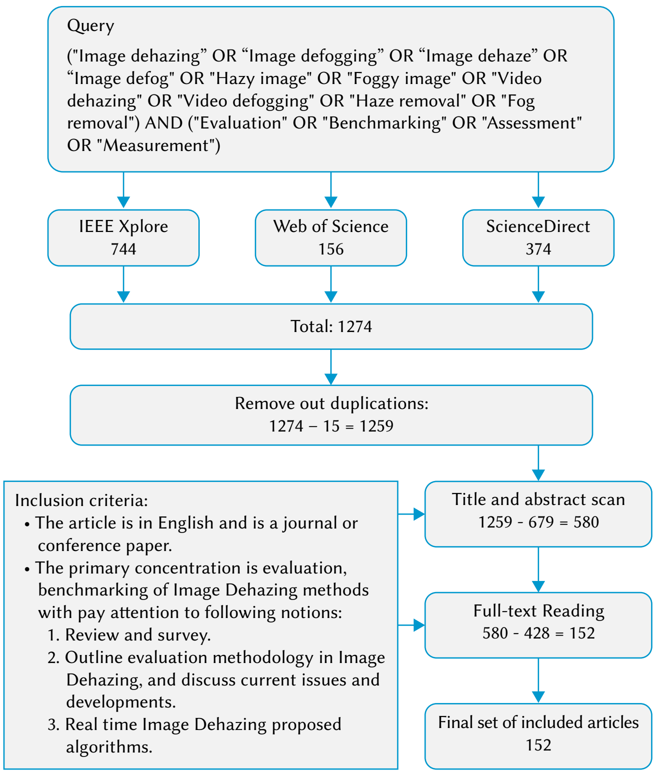

Fig.1. Study selection diagram.

D. Eligibility Criteria

Entire articles that match the criteria shown in Fig. 1 were included. We set the primary goal as mapping the compass of research on image dehazing into a wide-range and coarse-grained taxonomy of three groups. The groups were procured from a comprehensive pre-review of the existing literature with no restriction. To eliminate replicated articles, we excluded the articles that failed to match the eligibility criteria. The exclusion criteria covered the following consecutive points: (1) the article is non-English; (2) the focus is on limited aspects of image dehazing, such as non-real-time methods.

E. Data Collection Process

The well-known EXCEL® software was employed to coordinate the final set of articles that was assembled through the study selection with the corresponding initial categories. We achieved multiple full text readings of the articles included to underline the importance of details and comments on the revised studies and in a running classification of articles in a polished taxonomy. The highlighted details and comments were found in the body of the texts (corresponding to the authors' desired style). The significant outcomes were summarized, tabulated, and described. Word and Excel forms were used to save information, such as article lists, relevant online source databases, summary and description tables, study types, review sources, utilized datasets, dataset types, evaluation types, evaluation metrics, and different related figures. These details were presented in a manner in which the auxiliary materials could serve as a full reference for the results. They are defined in the next section.

III. Results

The first run of the search query filtered 1274 articles with the following details: 744 articles from IEEE Xplore search engine, 374 articles from SD, and 156 articles from WOS over a period of 13 years (2008–2021). Fifteen articles were duplicates. Through title and abstract scanning, 679 articles were excluded as non-related ones, resulting in 580 articles. After the full text reading step, 428 articles were excluded. Finally, 152 articles were included in the final set of articles. These articles were examined carefully to obtain a generic research overview of this emerging area. Nevertheless, a variety of studies have focused on the same area. The articles were categorized on the basis of the aim of the study and utilized to serve the process of taxonomy formation. Fig. 2 shows the proposed taxonomy for reviewing the research articles that focused on image dehazing. Consequently, three types of article categories were identified in the obtained taxonomy. First, out of 152 articles, only 55 of them focused on various studies on image dehazing, such as the comparative study of different image dehazing algorithms, multiple evaluation methods and proposed metrics, and different datasets based on diverse scenes and circumstances. Second, 13 studies conducted a review and survey, reviewing different aspects such as multiple methods based on dark channel models, underwater image dehazing metrics and methods, suitable methods for driver assistance systems, and comprehensive investigations into the image dehazing field. Third, 84 articles were focused on the development of methods for real-time scenarios.

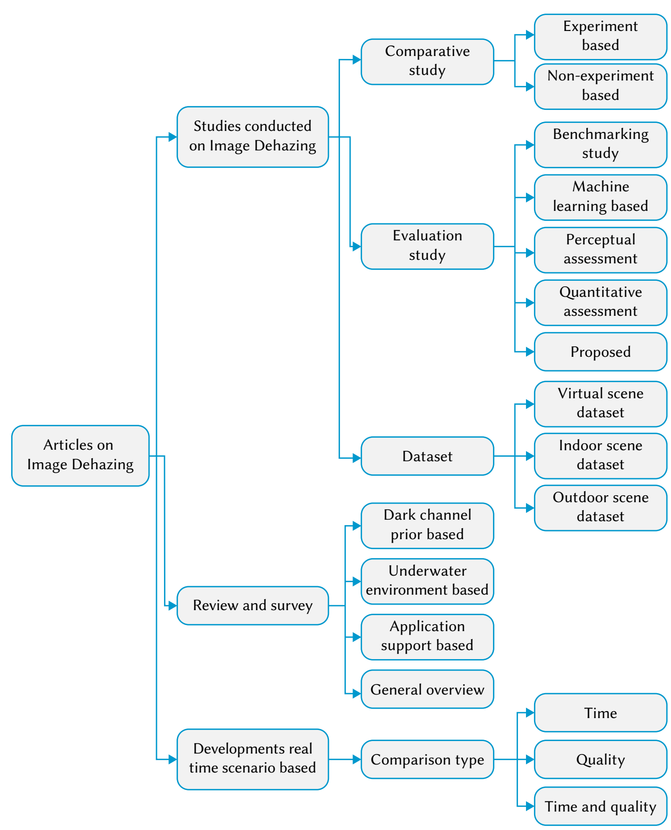

Fig. 2. Taxonomy of research literature on image dehazing.

Through outlines, we indicated the generic categories of articles and revised the classification into a literature taxonomy, as shown in Fig. 2. In this figure, we also illustrate numerous subcategories of the main classes without any overlap. The following sections describe the perceived categories and provide simplified associated statistics.

1. Studies Conducted on Image Dehazing

Generally, the image dehazing literature focuses mainly on the development of new methods. The second largest article group comprises diverse studies (55/152) on image dehazing.

We divided the works included into three main subcategories: comparative study (3/55), evaluation study (18/55), and dataset-based study (34/55). Comparative studies are experiment-based [13], [26] and non-experiment based studies [27]. Three studies compared the prevalent approaches in this area through the implementation of methods and using the most common parameters for critical analysis. One study compared several well-known visibility enhancement techniques without further implementation.

More articles are found in the evaluation category (18/55), which is basically introduced through different evaluation types and techniques. A new direction in the image dehazing domain has been presented in the recent years by authors in [28]-[30], where image dehazing algorithms are evaluated and selected based on principle of multi-criteria decision making (MCDM). An evaluation study [31] compared the performance of different techniques for underwater autonomous vehicles, with the preferred characteristics being the reduced need for additional hardware, short computation time, and simple inputs. Machine learning techniques for assessing the quality of dehazed images were introduced in two studies that respectively presented a novel quality assessment framework for the performance ranking of image dehazing algorithms [32] and a relative quality ranking between enhanced images instead of absolute quality scoring for a single enhanced image [33], [34]. Existing works reported that image quality assessment methods are mainly divided into two types. The first type is subjective (perceptual) assessment involving psychophysical experiments in which human observers are asked to grade a set of images according to a given quality criterion to offer agreement among observers on the quality of haze-free and dehazed images [35], [36]. The other type of well-known image quality assessment is quantitative (objective) assessment, which is the essential element in the evaluation of perceived image quality [37]. Quantitative evaluation is more structured and reliable than subjective evaluation. This tool usually uses the objective criterion and offers an identified procedure for measuring image quality. Moreover, this method deals only with numeric results, and any user who wants to use this method will obtain the same result [22]. Even with the popularity of quantitative assessment, other consistent methods of objective evaluation must be developed to provide accurate judgements on image dehazing algorithms [24]. Finally, several methods and metrics of image quality assessment have been proposed. First, a method was developed on the basis of the circularly symmetric Gaussian normalization procedure's visible edge feature, which does not require exposure to distorted images priori and training [23]. Second, a quantitative assessment method based on two optimization objectives was introduced with consideration of several aspects for evaluation, such as the effects of color distortion of the dehazing process and halo artifacts in restored images [38]. Third, three new methods (contrast measurement index (e), image naturalness index (CNI), and colorfulness index (CCI)) were combined to assess the defogging algorithm [39]: a new metric based on underwater scattering and absorption aspects [40], an evaluation metric combining contrast degree with structural similarity [41], and a novel no-reference haze assessment method based on haze distribution for remote sensing images [42].

In terms of support for the evaluation process and development of new image dehazing algorithms, the largest group of articles have been found in the datasets category (34/55) which are presented in three forms. The virtual scene dataset was basically created by utilizing computer graphics to produce an enormous number of hazy images (2000 images) based on road scenes with different levels of fog [43]. Indoor scene datasets were established through real scenes inside a room with a fog machine to generate 9 images [44], 1400+ images [45],and controlled underwater environment images using milk to obtain the turbidity in a water tank [46]. The outdoor scene datasets were designed with two scenarios, namely, a database that consists of natural scenes in uncontrolled outdoor conditions (5640 images [47] and 3464 images [48]) and a synthetic outdoor dataset created through synthesized haze in real images with complex and multiple scenes [49].

To enrich the development of image dehazing methods and the practice of image quality assessment, we reveal several types of datasets in this study. The variations of datasets depend on scene conditions and environmental domains. Scene types can be classified according to circumstances, such as indoor, outdoor, and road traffic scenes. The haze removal process requires two types of images, namely, hazy images for removing the noise and haze-free images for measuring the volume of enhancement. Thus, providing images reflecting various weather and illumination conditions, such hazy weather, foggy weather, poor illumination, and normal daylight, is a vital factor in the image dehazing practice. On the one hand, because atmospheric light varies between over-land and underwater scenes, some datasets are built on the basis of this context; examples include datasets of real underwater scenes [31] and synthesized datasets of underwater images taken in a water tank [40]. On the other hand, datasets have been classified according to whether they were built on real or virtual scenes. For real scenes, most images are taken using a camera based on indoor or outdoor natural images [47], [48], and these real scenes could be utilized for synthesizing new ones through different equipment for generating haze [45], [50]. For virtual scene-based datasets, images are usually generated using computer graphic techniques to render scenes [43], [51].

Further details on image dehazing datasets are presented in Table I. Our study provides several details about existing datasets, such as a reference using a dataset, total number of images, and sources and types of datasets involved. Although realizing different aspects of datasets is significant in image dehazing, multiple algorithms must be evaluated, and a new image quality assessment methodology must be proposed because authors are required to verify the efficiency of the developed methods in terms of enhancing and restoring images. Furthermore, the main goal of developers and researchers is to provide a public dataset that can be used for dedicated purposes, such as in validating and evaluating their methods.

Noticeably, image dehazing researchers are divided into two groups: those who built their own datasets and those who used public datasets or datasets from specific studies. In general, most researchers prefer natural outdoor scenes. Others favor the use of more datasets in their studies, specifically virtual and real image datasets. In terms of datasets based on a specific environmental domain, most existing datasets are on over-land scenes, and few are based on underwater scenes. However, most studies have widely used the FIRDA dataset because it involves different aspects, such as various kinds of foggy scenes (uniform, heterogeneous, cloudy, and cloudy heterogeneous fog), which can enrich the evaluation scenario from multiple perspectives. The dataset also presents a full reference scenario (clear and foggy images), which is the most desired aspect because achieving it is difficult in real world scenes and recording such images is not feasible due to the variations of illumination conditions [45].

TABLE I Dataset Statistics

Ref	Dataset	Over-land	Over-water	Underwater	Real	Synthesis	Indoor	Outdoor	Source
[31]	Dataset1 = 19 images (Rocks) Dataset2 = 94 images (sand and Rocks) Dataset3 = 100 images (shallow corals) Dataset4 = 99 images (medium corals) Dataset5 = 100images (deep corals)	×	×	✓	✓	×	×	×	[52]
[53, 54]	FRIDA dataset = 90 images FRIDA2 dataset = 330 images FRIDA3 dataset = 264 images (publicly available)	✓	×	×	×	✓	×	✓	http://perso.lcpc.fr/tarel.jean-philippe/bdd/frida.html
[6]	WILD (Weather and Illumination Database) dataset = 3000 images (publicly available)	✓	×	×	✓	×	×	✓	http://www.cs.columbia.edu/CAVE/software/wild/index.php
[55], [43], [56], [57]	Dataset (Fattal, 2014) 11 haze images (publicly available)	✓	×	×	✓	×	✓	✓	http://www.cs.huji.ac.il/~raananf/projects/dehaze_cl/results/index_comp.html
Frequency	-	79 %	3 %	17%	47%	50%	29%	61%	-

By contrast, the real image dataset of Fattal shares almost the same importance as the FIRDA dataset. In general, real images are more valid for real scenarios than synthetic datasets [45].

According to Table I and Appendix A, the majority of the existing datasets belong to over-land scenes where 79 % of datasets are constructed based on this type. Due to complexity of the environment and procedure to collect the data in underwater environment only 17% of datasets are founded belong to underwater scene. However, only one study was found that belongs to new direction in the construction of image dehazing datasets which is over-water scene. Regarding the evaluation experiment based on real and synthesis images; it was observed that only 3% are the differences where more articles were found to belong to synthesis type. Also, images based on outdoor scenes are much more than indoor images, where 61% of reported datasets belong to outdoor type.

2. Review and Survey

The review articles on image dehazing aimed to highlight new developments and provide a comprehensive view for image dehazing followers. The smallest article group in the taxonomy comprises the reviews and survey group of the literature (i.e., 13 out of 152 articles). These articles were classified on the basis of what the algorithms support, such as application support. Similar to this context, dark channel prior (DCP) is the most popular image dehazing model because of its adequate performance and potential for improvements and applications; the authors in [58] studied approaches on the basis of the DCP model. Three articles [59]-[61] reviewed the latest methods that have been effectively applied in the underwater environment, achieved good underwater image dehazing and color restoration performance with different methods, developed an underwater image color evaluation metric, and highlighted different underwater image applications. To find a suitable approach for vision-based driver assistance systems, an article [62] in the existing literature reviewed state-of-the-art image enhancement and restoration methods.

Most survey and review articles are based on the general view of image dehazing (7/14). These articles examined and summarized different methods of image dehazing, such as image enhancement methods, physical model restoration methods, and fusion-based visibility enhancement techniques [1], [2], [8], [63]. These methods were also categorized on the basis of the type of technique used to acquire information required by the image restoration process; examples include multiple image methods, polarizing filter-based methods, methods with known depth, and single-image methods [55], [64]. Finally, the authors in [6] reviewed the detection and classification method of foggy images and summarized the objective image quality assessment methods that have been widely used to compare different defogging algorithms.

Further analysis is presented in Table II which shows that most of the review articles on image dehazing were classified as other existing studies based on certain concepts. Several articles classified image dehazing algorithms into the following three forms on the basis of input type required by the dehazing process: single input image, multiple images, and additional information approaches [58], [55]. Fog, haze, smoke, mist, rain, and dust are weather conditions provided by a certain dataset, and according to these conditions, several datasets were classified [1], [2]. Most review studies focused

TABLE II. Critical Analysis of Review Studies on Image Dehazing

Ref	Input type	Dataset classification	Quality assessment	Application classification	Metric classification
[1]	×	✓	×	×	×
[2]	×	✓	✓	×	×
[6]	✓	×	✓	×	✓
[8]	✓	×	✓	×	✓
[58]	✓	×	×	×	×
[59]	×	×	×	×	×
[60]	✓	×	✓	✓	×
[62]	×	×	×	×	×
[63]	×	×	✓	✓	×
[64]	✓	×	✓	×	×
[55]	✓	×	✓	×	×
[61]	✓	✓	✓	×	✓
[65]	×	×	✓	×	×
Frequency	**53%**	**23%**	**69%**	**15%**	**23%**

TABLE III. Critical Analysis of Real-time Image Dehazing Algorithms

	Approach					Evaluation		Data type				
Ref	Image restoration	Image enhancement	Image fusion	Hybrid	Technique	Subjective	Objective	Image	video	Image and video	Scene type	Application support
[5]	✓	×	×	×	Gaussian surround filter and DCP	✓	✓	✓	×	×	General	Not specified
[9]	×	×	×	✓	Anisotropic diffusion	×	✓	✓	×	×	General	Not specified
[86]	✓	×	×	×	DCP and gray projection	×	✓	×	×	✓	General	Not specified
[107]	✓	×	×	×	Machine learning	✓	✓	✓	×	×	General	Not specified
[108]	✓	×	×	×	Machine learning	×	✓	✓	×	×	General	Not specified
Frequency	70%	10%	2%	16%	-	23%	95%	80%	5%	13%	-	-

on classifying approaches and methods for image dehazing, whereas several studies presented an image quality assessment of certain haze removal algorithms [55], [64]. Many applications have taken advantage of employing image dehazing algorithms as a preprocessing step, but only a few studies have classified the applications related to this area [60], [63]. Finally, in terms of criteria for evaluation of certain image dehazing algorithms, numerous metrics have been reported in the existing literature, but few studies have classified these metrics according to the most critical evaluation criteria [6], [8].

However, input type is an important aspect of image dehazing in terms of defining the complexity of steps and the type of procedure to define the transmission map or estimate the airlight. Table II shows that many studies (53%) have considered input type as a classification aspect. Furthermore, few studies (23%) have considered types of weather conditions that should provide through experiment of data acquisition, thus presenting more complex scene is very beneficial in efficiently verifying the performance of multiple image dehazing algorithms. In this direction, our study presents many types of datasets and more information about these datasets (see Table I), enabling other researchers to select the most appropriate one for a particular study. Moreover, quality assessment is a vital step in evaluating the performance of certain algorithms, and it facilitates the selection of the best algorithms for specific scenarios. In this direction, many studies (69%) have highlighted the types of evaluation approaches and discussed details of the evaluation. In addition, many applications have been based on the image dehazing concept, but only a few studies (15%) have classified these applications. In addition, providing an umbrella for the types of metrics that can be used for evaluation scenarios is significant; it can also define the most suitable metric for a specific case study. However, only few (23%) studies considered this matter.

3. Development of Methods Based on Real-time Scenario

Apparently, most research works on image dehazing are development articles (84/152) dedicated to improving the process of dehazing through the enhancement of the quality of degraded images and the increase of the speed of restoration. Typically, proposing a new method requires an evaluation process to measure the effectiveness and efficiency of the proposed approach. Thus, in the current work, new algorithms of image dehazing were compared with other algorithms in terms of execution time and quality. We classified development articles according to comparison details provided through the literature, especially in the quantitative evaluation section. A total of 11 out of 84 articles mentioned time as the sole evaluation criterion; it is the most preferred indicator in real-time scenarios [66], [67]. A total of 10 out of 84 articles stated quality as the performance comparison metric [51],[68]-[70]. Finally, most comparison settings are based on time and quality criteria, that is, 60 out of 69 articles. As shown in Table III, articles were classified into many aspects. First, numerous algorithms support certain types of applications, such as driver assistance systems [71]-[73], road sign detection [74]-[76], monitoring of power plants [77], optical systems [78], surveillance applications [79], [80], embedded systems [81], unmanned aerial vehicles [82], and car vision [83]. Second, some algorithms concentrate on hardware implementation or utilize a specific hardware architecture, such as heterogeneous multi-cores [71], field-programmable gate arrays (FPGAs) [81], [84], and a seven-stage pipeline hardware architecture [85]. Third, through experiments, several types of data were examined, and they include image and video [86]-[89], video sequence only [90], or image only [91], [92]. Fourth, as mentioned, the evaluation of a certain algorithm was divided into two types, namely, subjective and objective; most algorithms were objectively evaluated [93], [94], and only a few studies adopted a subjective approach on the basis of user observations that rate the perceived quality of tested images [5], [87], [95], [96]. Fifth, image dehazing algorithms were proposed using different approaches and techniques. These approaches could be based on a physical model [9], [93], a non-physical model [97], image fusion [98], [99], and approaches that combine image enhancement and restoration [100], [101] or image restoration and fusion [102], [103]. Finally, because of the satisfactory performance of the DCP, it has been adopted in many image dehazing algorithms [89], [104]. Moreover, only a few algorithms have been based for other techniques, such as machine learning [105], [106].

According to the **Table III and Appendix B**, due the advantages of depth estimation for image dehazing physical model most of the studies (70%) are conducted based on restoration approach. Minimal studies have adopted other approaches such as image enhancement (10%) and fusion (2%).

However, a new trend is presented by few studies (16%) that used the image restoration approach relative to image enhancement or image fusion. In some cases, these studies leveraged the image enhancement procedure as a post processing step with image restoration or image fusion. Furthermore, because of its simplicity and speed, DCP (model) has been widely employed in image dehazing algorithms. In terms of evaluation, most researchers only (23%) try to avoid the subjective method, which involves user opinion, because of its disadvantages. They tend to prefer to deal with the structured method, which involves specific criteria (objective method) where almost 95% of articles are include a quantitative evaluation approach. In terms of data tested with the algorithm, images have been widely used (80%) because they require less processing than videos (many frames) do. Only a few studies involved special hardware implementation, such as FGPA, to provide full real-time scenarios that are based on embedded systems. Finally, as mentioned in the Motivations section, the image dehazing principle has been widely adopted in various applications. However, the types of application supported by many algorithms are not specified, thus contributing to the difficulty of selecting a suitable algorithm for certain applications. To mention, most of the existing studies are preferred to use general hazy scenes in other word more than specific hazy images such as inhomogeneous, homogenous, dark, and sky in order test the validity of certain proposed algorithm. On other hand, some algorithms are dedicated for enhancement of specific hazy image such as sky or inhomogeneous or daytime rather than night-time. The most surprising part is that the principle of image dehazing is used in different case studies that not involved real haze characteristics such as TV industry, Biometric, Steganography, and nondestructive testing (NDT). Meanwhile, several algorithms support driver assistance systems, agriculture monitoring, railway industry, mobile cloud of smart city, and so on. Therefore, existing algorithms need more experiments on video datasets to validate their performance in terms of frame sequence processing and on more embedded systems to verify their suitability for real-time applications. Similar to other researchers, we recommended the use of objective evaluation rather than subjective evaluation.

To highlight and understand the trends in the research literature, which is one of our study's contributions, Fig. 3 illustrates the number of publications gathered from the literature along with the corresponding search engine types and presents further content analysis. The statistics for the articles are covered in the final set (152). As shown in Fig. 3, significant attention was given to the development of new methods for image dehazing using real-time scenarios.

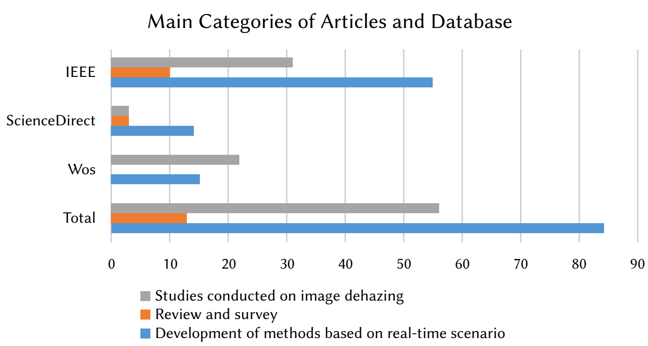

Fig. 3. Number of articles by their main categories and database sources.

Fig. 4 specifies the number of articles according to category and year of publication. Apparently, significant efforts have been exerted to explore image dehazing in recent years, particularly in development studies and review and survey articles. As mentioned previously, studies on image dehazing showed 55 papers, the review and survey category showed only 13 articles, and the category on the development of real-time scenario-based algorithms showed 84 articles.

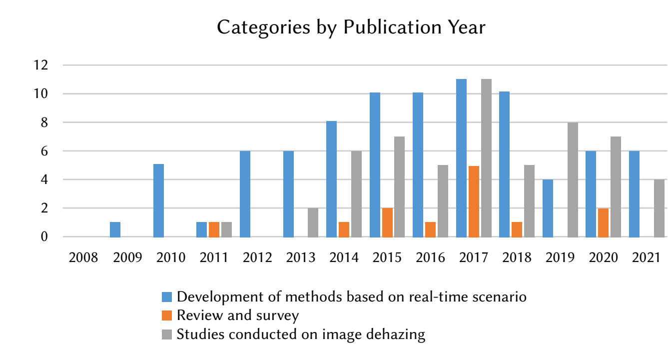

Fig. 4. Number of articles in each category by year of publication.

Fig. 5 shows the distribution of articles within each country. China was the country more focused on image dehazing with 74 contributions from different Chinese organizations and universities. This could be relevant to existence of bad weather during different seasons as well as the smoke or haze emission from factories. However less attention for image dehazing topic has been found by different countries such as Australia, Austria, Canada, Norway, and so on.

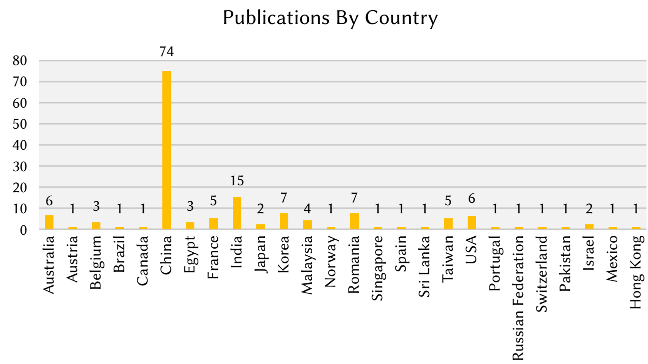

Fig. 5. Number of articles according to country.

IV. Evaluation of Experimental Results

In this section, some image dehazing algorithms were compared via image quality assessment experiments. Seventeen image dehazing algorithms are included in this experiment such as **Dehazenet** [68], **MSCNN** [140], **Colores** [141], **Zhu** [4], **Multi-band** [142], **CO-DHWT** [143], **Meng** [144], **Liu** [145], **Berman** [146], **BF** [147], **WBCID** [148], **GF** [149], **JBF** [150], **Kim** [184], **NHR** [151],**He et al.** [10], and **Tarel** [152].The evaluation experiment is conducted based on the two datasets LIVE Image Defogging Database [81] and RESIDE [66]. According to [6], [28], [29] the evaluation of image dehazing algorithms based on different hazy scene characteristics provides comprehensive image quality assessment. Thus, the potentials of a certain algorithm can be measured with different and more complex scenes. Along with this, four main evaluation scenes are included in our experiment namely inhomogeneous foggy scene, homogeneous foggy scene, dark foggy scene, and sky foggy scene (see Fig. 6 and Fig. 7). Also, the evaluation criteria are selected based on recommendation from other studies specifically [6], [24], [25]. These criteria are divided into quality and time. Where each algorithm will be measured based on exaction time and each of e, r, Σ, HCC, SSIM, and UQI. Further details about criteria can be founded in the three mentioned references.

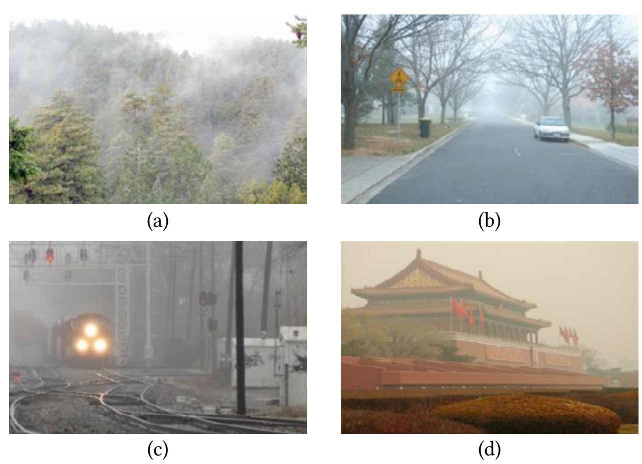

Fig. 6. LIVE Image Defogging Database: (a) inhomogeneous foggy scene, (b) homogenous foggy scene, (c) dark foggy scene, and (d) sky foggy scene.

(a) (b) (c) (d)

Fig. 7. RESIDE Database: (a) inhomogeneous foggy scene, (b) homogenous foggy scene, (c) dark foggy scene, and (d) sky foggy scene.

According to the Table IV, WBCID algorithm scored the best performance only in each of SSIM, UQI, and Time complexity. On other hand, Tarel have shown the best performance in terms e and Σ criteria. However, all other algorithms have scored better performance than WBCID and Tarel in other criteria.

However, **Appendix C**, NHR algorithm scored the best performance only in each of e, and r. On other hand, WBCID have shown the best performance in terms UOI and time complexity. However, all other algorithms have scored better performance than NHR and WBCID in other criteria. Furthermore, **Appendix D** showed Tarel algorithm scored the best performance only in (e) criteria. Also this algorithm share same performance level with Kim method. However, all other algorithms have scored better performance than Tarel in other criteria. Moreover, **Appendix** E stated that GF algorithm scored the best performance in each of SSIM and UQI. However, all other algorithms have scored better performance than GF in other criteria. Tarel, Kim, WBCID, CODHWT, and Zhu have same performance value in color saturation metric (Σ). Besides, **Appendix F** exhibited that NHR algorithm scored the best performance in each of e and r. However, all other algorithms have scored better performance than NHR in other criteria. Other algorithms such as JBF and WBCID have same performance value in color saturation metric (Σ). Also, **Appendix G** presented that NHR algorithm scored the best performance in each of e r, and UQI. However, other algorithms have scored better performance than NHR in other criteria. All other algorithms such as Dehazenet, MSCNN, Zhu, Multiband, BF, WBCID, Kim, and Tarel algorithms have same performance value in color saturation criteria (Σ).

In **Appendix H**, all algorithms scored the leading performance within distinct criteria. Other algorithms such as Zhu, WBCID, and Tarel algorithms have same performance value in color saturation criteria (Σ). Finally, **Appendix I** displayed NHR algorithm scored the best performance in each of e and r. However, all other algorithms have scored better performance than NHR in other criteria. Other algorithms such as MSCNN, Zhu, Kim, and Tarel algorithms have same performance value in color saturation criteria (Σ).

V. Discussion

This study mainly aims to provide a holistic view of recent trends and issues in image dehazing. This review is also unlike other reviews because it utilizes a systematic approach (protocol) in collecting pertinent works on image dehazing. Furthermore, it offers a taxonomy of correlated literature.

Nonetheless, a noticeable leverage of developing a taxonomy for the literature exists in the research domain, particularly an emerging one. In this context, a taxonomy of the existing literature brings a well-organized approach for a series of publications. For instance, a researcher who attempts to investigate image dehazing trends may be disappointed by the huge number of designated articles for a relevant topic that do not encompass any type of structure. In this case, the researcher could fail to obtain insights into the current scenario in this field of study. Most studies approach topics from an introductory perspective, others highlight a volume of existing methods and evaluation approaches, and some offer new image dehazing algorithms and propose new metrics for the field. In addition, a taxonomy of the related literature facilitates the organization of numerous works and activities into an expressive, controllable, and well-knit scheme. Furthermore, a well-structured taxonomy is beneficial to all researchers with respectable views on the subject field in a number of ways. First, a taxonomy provides prospective guidelines of research in the field. For example, in this study, the taxonomy of

TABLE IV. Evaluation Results Based on Inhomogeneous Foggy Scene (Live)

Algorithm	e	r	Σ	HCC	SSIM	UQI	Time
Dehazenet	11.029412	1.318396	0.0016	-0.0693	0.8629	0.8337	2.4931
MSCNN	10.925098	1.4033	0.0027	0.7857	0.8982	0.9127	2.1131
Colores	11.400392	1.4669	0.0347	0.0065	0.8507	0.8309	1.3199
Zhu	11.253725	1.4080	0.0016	0.0043	0.8748	0.8997	2.4770
Multi-band	10.931765	2.8822	0.0376	-0.0331	0.5932	0.7509	0.9475
CODHWT	4.988627	1.255105	0.002373	**0.844508**	0.950891	0.945836	2.331291
Meng	14.095686	2.091165	0.034902	-0.121426	0.68192	0.698885	5.865411
Liu et al.	5.362353	1.583764	0.004549	-0.158128	0.641053	0.59172	1.171679
Berman	7.902745	**3.310823**	0.061231	-0.041326	0.55014	0.706861	11.24844
BF	8.451373	1.355124	0.0415	0.1308	0.9457	0.9842	5.4083
WBCID	16.463137	1.050864	0.0031	0.4681	**0.0529**	**0.6189**	**0.8715**
GF	7.902745	1.305597	0.0441	0.1212	0.9462	0.9892	3.8475
JBF	7.607059	1.190982	0.0345	0.1306	0.9585	0.9710	2.8108
Kim	8.991765	1.151766	0.0010	0.1106	0.9477	0.9668	1.6117
NHR	7.32	3.223612	0.1326	0.0398	0.6632	0.9246	35.8466
He et al.	6.157647	1.561816	0.0990	0.0657	0.8792	0.9880	21.0095
Tarel	**25.379608**	2.593767	**0.0001**	-0.0325	0.6911	0.8651	4.8757

image dehazing shows researchers the level of interest in developing new real-time methods; in turn, researchers could notify others about the development of image dehazing applications. Therefore, a potential direction may contribute to this area. Moreover, such an overview could facilitate the assessment of current image dehazing methods or the exchange of experiences in developing new image quality assessment methods. Meanwhile, taxonomy helps expose open issues in the available image dehazing assessment methods, that is, it outlines the articles on image dehazing into discrete classes, thereby providing a chance to investigate weaknesses and strengthens in terms of research coverage. For example, as many studies have highlighted, "to date, there is no acceptable image dehazing quality methodology." Combined with the developments of image dehazing methods in an adequate and representative sample of the literature, taxonomy also brings out several aspects of these methods, such as the execution time and accuracy of depth map estimation, which have received significant attention in the literature relative to traditional image dehazing methods. In addition, the statistics of individual categories of taxonomy highlight the environmental domains and the variety of real life applications that are based on the image dehazing concept. Nevertheless, to the best of our knowledge, most previous reviews were based on general aspects, such as categories of image dehazing algorithms. Thus, our taxonomy effectively exposes different concepts in image dehazing, such as evaluation and dataset study categories. Finally, researchers who are experts in this area can point out considerably to our taxonomy. If adopted, they can use a common language, thereby facilitating the sharing of future works and further discussions that cover areas such as development studies, new evaluation schemes, new datasets, comparative studies, and reviews on different image dehazing techniques and methods. Our study also reviews and identifies the different kinds of datasets used in the existing literature. We also illustrate different types of evaluation methods, such as objective and subjective methods, and the new evaluation metrics and methods.

However, the evaluation experiments revealed different observations. First, algorithms such as WBCID have leading performance in distinct criteria with different evaluation foggy perspectives in both examined datasets. In contrast, NHR algorithm have best performance in visibility criteria (e and r) within three foggy evaluation scenes, but only in evaluation based on RESIDE dataset. Second, the best performance for a certain algorithms cannot be achieved with more than three criteria. In other word, most of the leading algorithms have best performance in few criteria with distinct foggy evaluation scene. Third, some algorithms have shared same performance value in distinct criteria and foggy evaluation scene. Fourth, overall there is noticeable variation in the performance of each algorithm within each distinct evaluation scenario. Fifth, based on evaluation experiments in one or both datasets, there is no single algorithm have scored the best performance within all criteria as well as evaluation foggy scenes. Thus, due to performance confusion of all examined algorithms; selection of the best image dehazing algorithm is a challenging task. Therefore, our evaluation experiments confirmed the views about the selection problem that have been revealed by [6], [24], [25].

According to existing studies, the next sections describe three aspects of the literature content, namely, the motivations behind adopting image haze removal algorithms; the challenges and obstacles of developing image dehazing algorithms, evaluation methodologies, and datasets; and recommendations to mitigate such hurdles.

A. Challenges

The haze removal process and quality evaluation for degraded images are still highly challenging. Image defogging is a transdisciplinary challenge because it needs information from various aspects, such as meteorology for demonstrating mist, optical physics science for observing the manner by which light is influenced by haze, and signal processing for recouping the parameters of scenes [44]. According to investigations in the existing literature, several obstacles exist and require substantial efforts from researchers and developers to permanently align the image dehazing process with adequate restoration and enhancement results. The challenges illustrated in the literature and the citations of relevant references are discussed below. Additionally, the challenges are classified into several groups, as shown in Fig. 8.

1. Data Acquisition Challenges

Due to haze is an outdoor phenomenon, factors such as weather condition, dynamic objects, and so on have made data acquisition a hard task. This subsection presents obstacles relevant to data acquisition into image dehazing domain as follows:

a) Absence of the Haze-free Image (Ground-truth)

The assessment process for perceived image quality, especially with full reference metrics or decreased reference ones, may need two types of images, namely, hazy and haze-free images, which are taken

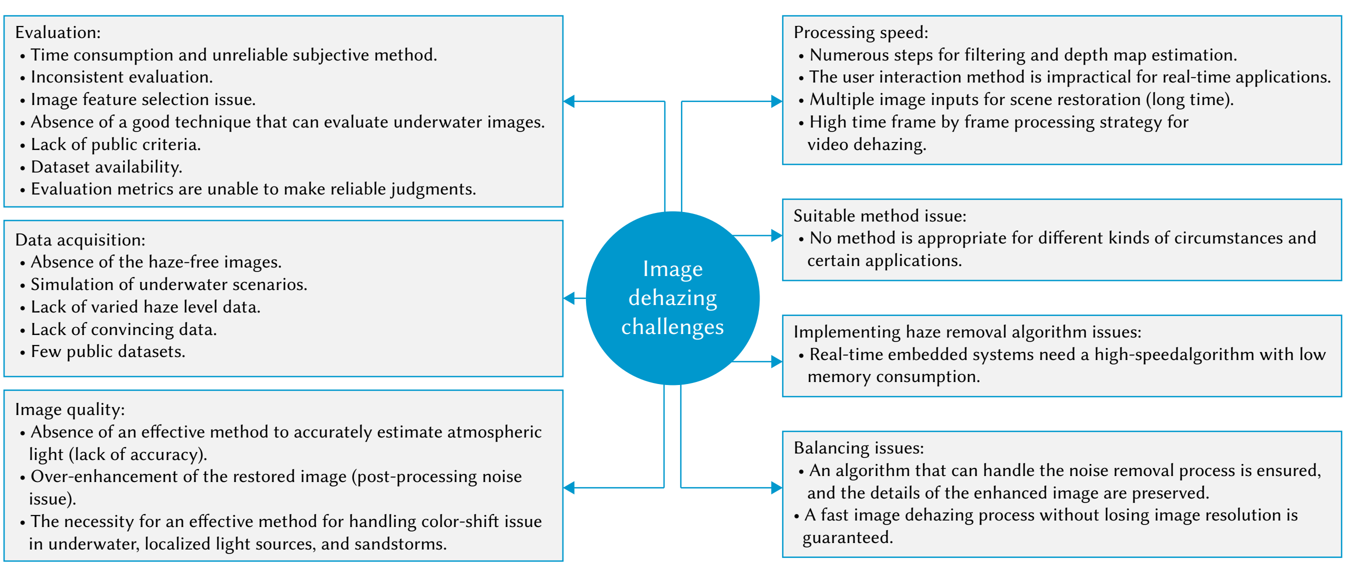

Fig. 8. Categories of challenges for image dehazing.

under the same real scene settings and weather conditions [44]. Most datasets do not include images as a reference because these types of graphics are difficult to provide, thereby resulting in major difficulties in presenting an efficient evaluation process. The procedure of recording haze-free (reference) and hazy images in similar illumination conditions is still highly challenging [36],[43]-[45],[55].

b) Reproduction of Underwater Environment Characteristics

Fundamentally, light that travels through an underwater medium loses its intensity because of attenuation. Attenuation is limited to the type and number of existing particles in the turbid medium. These phenomena are due to two aspects, namely, absorption and scattering [109]. Absorption completely eliminates light beams, whereas scattering alters the course of the light spread. Simulating these phenomena is difficult because they occur due to specific particles and properties present in oceans, rivers, and lakes. Another challenge is related to the reproduction of an untouched seabed in a controlled space with specific underwater properties [46].

c) Lack of Datasets on Different Haze Levels

Image haze removal has been extensively studied, but no such image database regarding haze levels is present. Verifying the assumptions or priors that are supposed to be useful for haze removal is inconvenient for readers. Meanwhile, comparing the performance of haze removal methods, which are effective for images with different haze levels, is inappropriate. Haze level determines the amount of contrast and other details regarding a particular image [48].

d) Synthetic Image Database Issue

The FRIDA dataset [110] was based on virtual road scenes developed using computer graphics techniques. This dataset includes 66 images because of the diminished complexity level in the scenes, and some parameter settings are ineffective for real life circumstances, thereby making it less convincing for evaluation [45].

e) Lack of Benchmarked Dataset

According to [32]-[33], no public benchmark dataset on image defogging is available for comparing the performance of many enhancement algorithms.

2. Evaluation Challenges

In general, a quantitative assessment of dehazing algorithms based on a single input image is unlike other image processing methods. According to [22], several issues have been highlighted by authors in terms of the method's ability to decide on a highly enhanced image by a specific algorithm, and the answers of numerous evaluators are often inconsistent. Moreover, approving and choosing the accurate haze removal result for a particular situation is difficult. The common image quality assessment methods seldom provide solutions to these problems. Likewise, procedures that can effectively measure the quality of dehazed images using a specific algorithm are lacking [24]. Moreover, objective quality assessment methods are rarely used because they are unable to make reliable judgments [64]. The existing literature reports that no generally accepted methodology for evaluating image dehazing performance is available [36], [49], [32], [39], [22], [106]. The lack of an acceptable evaluation methodology can be classified according to following issues:

a) Subjective Evaluation Methodology Issues

Developing methodologies for evaluating such algorithms with regard to their perceptual quality is necessary. Measuring the perceptual quality of a contrast enhancement method applied to images degraded by fog is a nontrivial task, and no agreed-upon methodology currently exists [35]. The well-known solution is hand posting various degraded images and their relevant enhanced ones, which are processed by diverse algorithms, and then subjectively comparing them. However, the quantity of listed images is bounded; thus, reporting an algorithm that effectively performs in these listed images is difficult, and performances are still unknown in other cases [33]. Moreover, a subjective evaluation could include emotional responses and subjective judgments of a particular observer. Therefore, a pair of observers may end up with dissimilar or dissonant results on the same tested image [2]. Thus, human bias is allowed, and using a subjective evaluation method is expensive and time consuming, thereby making it unsuitable for real-time applications [33], [75].

b) Lack of Evaluation Consistency

Although substantial research has been conducted on image dehazing, evaluation methods presenting satisfactory results are still lacking [38]. The defogging effect assessment is difficult because the evaluation criteria for the defogging effect should be consistent with human visual perception. Image quality assessment metrics, such as mean square error and peak signal-to-noise ratio, have been widely used to assess dehazing algorithms. However, these indicators often obtain inconsistent results [39]. Moreover, comparing single indicator scores and utilizing a regression-based prediction model are inconsistent with the human visual perceptual mechanism [32], [89]. Thus, developing an evaluation method that can possibly cross over any barrier between computable assessment models and human visual perceptual mechanisms is challenging [22].

c) Appropriate Image Feature Selection

Extracting truly intrinsically salient features to define hazy images and differentiate hazy-free images from non-hazy ones is one of the evaluation challenges [32]. In addition, computational efficiency is important; thus, the features need to be immediately extracted [6].

d) Unsuitability of Evaluation indexes and Methods for Some Scenarios

According to [46], an efficient evaluation technique for underwater images is lacking. Scattering and absorption are two main issues when light travels in an underwater environment, which generates different kinds of distortions for an underwater image. One issue is color loss due to light absorption in the water. Scattering also is another issue that usually affects image details, thereby blurring image edge information and diminishing image contrast. However, utilizing (over land) atmospheric image quality assessment metrics to successfully evaluate the quality of an underwater image is difficult because of contrasting imaging concepts [40]. In [111], few metrics were developed for the evaluation of underwater images. Dehazing algorithms are aimed at achieving high image visibility (contrast) and structuring similar images. Specifically, the perceived quality of an enhanced image should match the non-hazy one (sunny day) in terms of contrast and structure. Additionally, using brightness as an evaluation metric is ineffective because the brightness of a dehazed image is different from that of a sunny one [41].

e) Lack of Public Criteria

The human visual perception itself is not a deterministic procedure. Thus, deciding the highly vital features that influence visual decision and designing corresponding evaluation metrics are difficult [39]. For the evaluation of image dehazing algorithms, the authors found that no public criterion and dataset are available for reference [33]. Moreover, no perfect criterion can effectively evaluate the quality of a perceived dehazed image [6], [8], [33].

f) Desired Dataset Availability

Different assessment techniques have been generally accepted; thus, having a highly reliable dataset is important [45]. The quality assessment for numerous algorithms has become extremely challenging due to the lack of perfect images to be used as a reference

[36], [39], [43], [44], [55], [89]. Furthermore, no public benchmark dataset for image dehazing that can be used for the evaluation process is available [32], [41].

g) Lack of Reliable Indicators

A solid image quantitative assessment metric that can viably gauge the quality of an enhanced image and the amount of information loss in restored graphics is current not available. Developing a highly reliable framework of metrics that can present a satisfactory performance for image quality assessment is a challenge because the current quantitative assessment metrics are unable to make dependable judgments [24].

h) Suitable Method Issue

Many researchers have ignored several issues in the image dehazing field. For instance, no suitable method is available for different kinds of conditions [27]. The authors reviewed some underwater image processing methods to guide other researchers in determining highly suitable techniques or methods for a particular application [31], [59]. In addition, categorized enhancement techniques based on several approaches have been used to enhance and restore hazy images and then select the appropriate algorithm for certain needs [1], for example, reviewing various methods for highlighting the suitable scheme for a driver assistance system [62].

3. Processing Speed Challenges

Methods dedicated to work in real-time applications usually need fast computation. In general, a time-consuming process is an undesirable and highly challenging problem in real-time scenarios. Many studies have been proposed to address this challenge [9], [66], [69], [86], [112]. The high computation algorithm problem could be due to the following issues.

a) Complex Computation Processing

The haze removal process becomes challenging because of unknown depths and its dependence on defined depth (transmission) maps for scenes [113]. The desired atmosphere veil should always be refined [94]. A full dehazing process consists of three complex computation steps (i.e., estimation of atmospheric light, acquisition of atmosphere veil, and restoration of a non-hazy image) [84]. The acceleration for refining transmission is a highly desirable aspect in many algorithms, such as bilateral [114], anisotropic, edge-preservation [115], and median [15] filtering, given that most image defogging algorithms need to decrease the complexity of filtration. The aforementioned algorithms are challenging to implement and apply in real-time systems [116] because they require considerable time to enhance restored images. Thus, having the minimum filtering steps is necessary for meeting real-time requirements [56], [84], [86], [94], [117], [118] restoring images without estimating airlight and transmission (depth) maps [98], [102], [103], or minimizing the time needed to calculate transmission maps [77], [69].

b) User Intervention

Depth-based methods need depth information either from known 3D models or from user interactions [119]. These types of methods are impractical to use in real-time applications because of their complexity and time-consuming nature [91]. In [120], a user must interactively register a weather-degraded image with a 3D scene model to dehaze the former. The necessary user intervention (the sky area requires to be marked out by hand) [121] and additional data for these methods make them impractical for real-time applications [96]. Many algorithms have been proposed to prevent this user interaction issue [9], [92], [93], [100], [102].

c) Multiple Image Issue

Multiple images based on the same scene were used in [3], and other ones that were taken in different weather conditions have been utilized as references for graphics that were obtained under clear weather conditions. Algorithms based on a multiple image approach are unsuitable for real-time applications [96] because of high computational complexity [122].

d) Video Processing Issue

To date, numerous efforts have been initiated to eliminate haze from single images. However, few studies have concentrated on video sequence processing. These haze removal techniques for video sequences mostly utilize a frame-by-frame strategy. In these approaches, the fundamental thought of most methodologies lies in the calculation of depth maps for degraded scenes through the use of multiple images under various climate conditions [80]. Moreover, the high time complexity of video dehazing occurs when utilizing a frame-by-frame strategy. Many methods have been designed with different strategies to prevent the time-consuming processing of the frame-by-frame strategy for achieving real-time video dehazing to address this efficiency issue [81], [82], [123], [124].

However, a fast execution time is an essential step for certain real-time video or image applications implemented in embedded systems. For example, considering a 30 fps video, the processing time of one frame in such a video must be no more than 0.03 s to meet real-time application requirements [72], [73], [85], [86], [97]. Therefore, an enhancement or restoration algorithm that can process 30 fps is suitable for real-time image applications.

4. Image Quality Challenges

a) Estimation Accuracy Issue

Airlight must be refined in terms of time, except for some regions wherein the depth map randomly changes because atmosphere veil essentially relies on the information of scene depth [94]. One of the crucial steps in image defogging is to provide highly accurate restored images on the basis of the accurate estimation of transmission maps. Despite the development thus far, an efficient method that accurately estimates the global atmospheric, which is a highly crucial part in the quality of image restoration, is lacking [68], [125], [90], [95].

b) Over-enhancement Issue

Many image dehazing methods, such as the DCP, based on a single image input have been investigated in the literature. The authors in [10] described the notion of dark channels on the basis of the thought that "in a clear day image, except for the sky regions, the intensity of each pixel will be close to zero at least in one color channel." This statistical observation is called DCP [5]. However, the image resulting from the restoration process exhibits missing details and suffers from unnatural coloring [58], and some haze remains at the edges of the images [83]. Specifically, the two main issues in the methods according to the DCP scheme are color distortion and generated halo artifacts in restored images [70]. Moreover, DCP cannot efficiently work with scenes that contain sky regions and white objects, under which it leads to a severe color distortion or blocking effect in restored images [58]. Thus, post-refinement processing is required to preserve image edges and efficiently restore color. Many methods have been proposed to effectively handle the defect generation of halo artifacts and color distortion to address the image darkening issue resulting from the restoration process [10], [50], [69], [86], [112], [126].

c) Color Distortion Issue

Color change is one of the main distortion issues for underwater images. The amount of color distortion increases according to the variation of the attenuation degree that the traveling light is exposed to [92]. Apart from the underwater scene, another scenario for color distortion is the localized light sources, which usually occur when car drivers turn on the headlights of their cars and streetlights are activated, thereby causing localized light in images that have been taken in these circumstances. Sandstorm is another weather circumstance that is normally experienced through driving in some areas. During a sandstorm, the atmospheric sand can absorb particular parts of a spectrum, thus producing color-shift problems in the taken image. In summary, the common up-to-date restoration algorithms are incapable of efficiently dealing with hazy images that feature color-shift problems or localized light sources [15].

5. Balancing the Noise Removal Process and Preserving Details of the Enhanced Image

Apart from the enhancement issues, one of the image dehazing obstacles is to guarantee the obtainment of a high-quality restored image without any image information loss. Balancing the decreasing defects resulting from the dehazing process while keeping the proper quality of restored images is difficult [23]. For example, the contrast of road scene images is considerably enhanced through the use of common image dehazing methods [75]. Moreover, a histogram equalization is used to increase the contrast of foggy images, but the quality is still extremely poor because noise increases as the image contrast improves [127]. In summary, the issue of balancing could occur between certain criteria, such as visibility and color fidelity [97], wherein an over-saturated image may present a high contrast gain but show a large number of saturated pixels [9].

6. Balancing the Quality and Speed of Image Restoration

Achieving a fast single image dehazing has been a challenging issue in many fields, such as real-time applications [89]. The existing literature shows that balancing computation time and quality of restored images is still an open issue [96] because providing a process that can offer a short time and present no image resolution loss (image details) for the image enhancement process is difficult [128]. Thus, restoring images to their natural conditions and ensuring the balance between the speed of image restoration and perceived quality are vital steps in the image dehazing process [69], [86], [116].

7. Issues in Implementing Haze Removal Algorithm

Most multimedia applications that require real-time processing currently rely on multi-core embedded systems because of their extraordinary data rate processing capabilities [71]. Real-time applications that support embedded systems usually need an algorithm that can handle several requirements, such as low memory consumption and fast processing (speed), of real-time scenarios. This scenario is challenging through the implementation of haze removal algorithms for image sequences on embedded systems [5], [71], [81], [129].

B. Motivations

Using image dehazing technology in various application domains and scenarios has numerous benefits. Thus, researchers are motivated to further improve image dehazing technology. This section demonstrates the multiple advantages revealed in the existing literature, which are classified in particular groups with corresponding reference citations (see Fig. 9).

1. Image Retrieval Benefits

In such situations, the intensity of reflected light from any scene point is usually attenuated as it travels to the camera device. In addition, airlight acts as the main source of illumination for all objects in the scope of the scene [130]. The major drawback of the abovementioned situations is the reduced image visibility, thus resulting in considerable

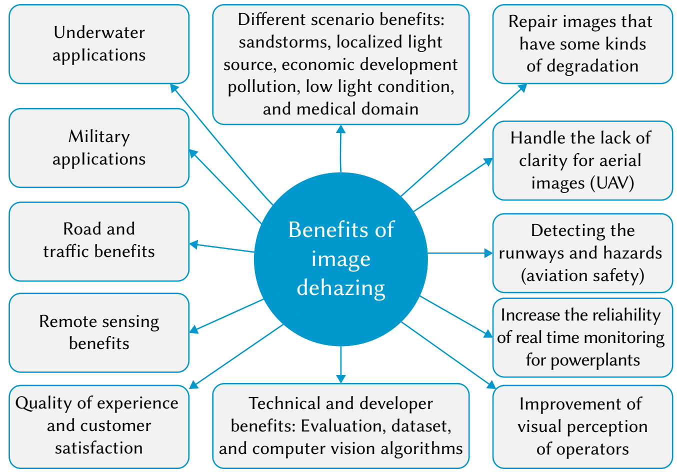

Fig. 9. Image dehazing motivation categories.

hindrances in various computer vision applications, such as image retrieval, photography restoration, and scene analysis [122], [128]. In general, image restoration methods have been made to overcome the defects of the quality of hazy images [46]. The notable feature of image dehazing is the restoration of image details, such as color [60] and contrast [86].

2. Military Applications

The quality enhancement of images obtained in foggy circumstances is a highly notable research area in military and civil applications [131], [42], [106]. UAVs are utilized for detecting (reconnaissance) and attacking intruded ground targets. The main drawback for this category of UAVs is the inefficiency of the object detection process, especially under turbid weather conditions, in which objects could hit the UAVs [132]. Thus, increasing the accuracy of detection is necessary to improve reliability.

3. Underwater Application Benefits

Underwater images suffer from tough color distortion and noise from artificial light sources, thereby resulting in image blurring and haziness [60]. In recent years, different underwater applications have been widely developed, with examples including documentation support and aircraft accidents. Fundamentally, remote-operated vehicles controlled by human experts are used to perform specific interventions. Highly advanced vehicles, namely, intervention autonomous underwater vehicles, have been recently developed, as described in [133]. One of the main disadvantages of AUVs is the necessity to understand the hostile environment to detect and recognize objects within obscured scenes. This condition is the motivation behind many studies that examined underwater image degradation to restore and enhance the visibility of underwater scenes [31]. Thus, the process of restoring the color of underwater degraded images will provide clear images for many underwater applications, such as the following.

- Monitoring marine biodiversity (exploration) [59].
- Underwater rescue (safety) [59].
- Detecting underwater pipeline leaks (pollution reduction) [59].
- Underwater microscopic detection [60].
- Terrain scanning (accurate terrain classification) [58], [134].
- Mine detection (safety of vessels and human lives) [60].
- Telecommunication cables (maintenance and tracking) [60].
- Coral image classification [135].
- Documenting underwater archaeology (shipwrecks) [136].

4. Road and Traffic Benefits

Fog is one of the critical factors of road accidents in bad weather conditions [27], [79]. In addition, road safety is considered one of the major issues in the transportation strategy of the European Union Commission [137]. In general, fog lessens the visibility of a scene, thereby affecting the visual quality of images [13]. For example, drivers cannot distinguish a road scene in foggy weather [26]. The demand for cameras and intelligent surveillance systems that execute real-time recording and monitor private or public areas is currently increasing. For example, consider a vehicle dashboard camera. Such camera records road situations in real time during driving, and the recorded videos can provide information for automatic license plate recognition [138] or data on crash-related events. Moreover, such information is highly beneficial for police investigating and resolving road incidents and traffic violations [137]. In intelligent transportation systems, cameras keep track of road or street scenes to detect traffic flow or identify cars for specific applications, such as vehicle identity checks. Therefore, video quality plays a critical role in such applications. However, unfavorable weather conditions or poor atmospheric light result in inadequate visibility in imaging systems and lead to the production of blurred video images, thereby rendering the recorded videos ineffectual. Defogging is a vital preprocessing technique for object detection in computer vision-based systems, and it has been widely used in outdoor surveillance system applications [85]. Furthermore, driver assistance systems take advantage of the increasing accuracy of detection and feature extraction through the availability of an image fog removal tool for the following processes: improvement of road-marking feature extraction and camera-based obstacle and circular road-sign detection [75], [76].

5. Different Enhancement Scenario Benefits

Different circumstances require image dehazing techniques to enhance degraded images. For instance, the manner by which image dehazing principles are used to decrease the color shift problem or distortion for two scenarios (i.e., localized light sources in images captured when drivers turn on their headlights and images taken through sandstorm weather) was observed [139]. Moreover, the authors considered image dehazing in videos taken under low lighting conditions to handle several particular issues, such as poor visibility and contrast [140]. The authors in [66] mentioned that fog is worsening in China as the economy develops. Most image recognition systems are suitable for normal weather, but the applications based on the restoration of degraded images are highly valuable.

6. Medical Domain

Recently, a new direction for image dehazing domain have been appeared where image dehazing theory can be applied for different case studies of medical area. For instance, the premature infants' retinal images are generally of lower visibility compared to adult retinal images, affecting the quality of diagnosis. Authors in [141] studied some image dehazing methods from general outdoor scenes and proposed an image restoration scheme for neonatal retinal images. Also, Medical X-ray image its quality digressed because of the interferences caused by the human body structure, equipments, and environmental factors. Authors in [142] ,verified that the X-ray image degradation caused by the X-ray scattering which is similar as the haze scattering.by applying dark channel prior method this challenge can be solved.

7. Consumer Market Benefits

Consumers prefer non-hazy images with high visibility details when shooting target objects. Consequently, image editing software or cameras that can restore scene details in hazy or foggy weather are highly beneficial for consumer marketplaces, and camera and camcorders increase customer satisfaction and reliability [55], [68], [91], [143]. Furthermore, televised transmissions of outdoor sports events, such as cross-country skiing or ski jumping, during hazy weather can seriously affect the quality of experience of television audiences [35].

8. Technical and Developer Benefits

a) Evaluation Benefits

According to the comparison result of various graphics, the quality of several enhanced images is poorer than that of hazy ones [36]. The manner of effectively comparing the performance of image dehazing becomes a novel task with the advancement of haze removal techniques in the past few years [32]. Thus, the evaluation process can present such an advantage in terms of measuring the effectiveness of enhancement quality for a particular algorithm against other ones.

b) Dataset Benefits

With regard to the evaluation of several algorithms and the development of a new one, providing clear images and supplementary datasets is highly essential to perform previous processes. Furthermore, a successful evaluation is obtained when we gauge the enhancement in processed (hazy) and reference (non-hazy) images [43], [44]. However, the formation of an outdoor scene is highly complex and relies on different atmospheric circumstances, such as mist, clear air, and fog. Thus, a large number of images are essential to study the complete variations of scene appearances. Datasets are used to reveal the importance of supporting the process of developing new algorithms for enhancing the visibility of degraded images for computer vision applications [45], [47], [48].

c) Computer Vision Algorithm Benefits

Many computer vision algorithms [144], such as image segmentation [145], annotation [146], and matting [147], are used when recovering a haze-free image from a bad one. On this basis, research on image dehazing has important and realistic importance [24], [125].

9. Remote Sensing (Measurement) Benefits

The evaluation of haze may facilitate recognition for images with extremely poor visibility to increase the reliability of remote-sensing image analysis. Remote sensing images offer substantial information about geographic and spatial areas and have been extensively used in hydrology, forestry [148], and weather forecasting [104]. However, all images that require remote sensing analysis easily suffer from the effects of haze on the visibility of specific scenes, thereby decreasing the value of remote sensing applications to a boundless level [42], [88], [98], [131].

10. Improvement of Visual Perception of Human Operators

In hazy weather, the severe degradation of the information captured by optical sensors usually occurs because of the scattering of atmospheric particles. Specifically, the attenuation of atmospheric light decreases the contrast and fidelity of images, thereby directly affecting the visual perception of the human operator vision system [77], [149]. Thus, studying the methods of image dehazing is necessary [86].

11. Power Plant Monitoring Benefits

Zones (i.e., near mountains) around plants frequently experience hazy weather due to their locations, thereby affecting the visibility of video monitoring. In addition, this type of noise affects the work of personnel, which involves extracting important information from certain videos, particularly in terms of line monitoring stations; brings enormous hazards to the information analysis process, and calls for early warning when wire line information is difficult to distinguish. Power lines should eliminate fog effects to increase the visibility of surveillance videos.

Furthermore, solving the foggy video problem is necessary to increase the reliability of power plant monitoring in real time [77].

12. Detecting Runways and Hazards (Aviation Safety)

The visibility of a scene decreases as the density of fog increases, thereby causing difficulties in aircraft take-off and landing (runway detection) [126], [150]. Thus, improving visibility and making images that are pleasing are beneficial for various applications, such as runway hazard detection [5].

13. UAV Benefits

Suspending particles usually produced by hazy weather easily affect the image formation process in UAV images [82], [63]. Hazy or foggy circumstances extremely diminish the visibility for the UAV imaging system, thereby resulting in a decreased reliability for UAVs. With regard to the extraction of important image features and target detection, low contrast and visibility are undesirable [151]. Thus, the aerial image defogging process in fog conditions is a highly beneficial aspect [152].

C. Recommendations

We also summarize many notable recommendations in the existing literature to support the image dehazing community in terms of diminished challenges and facilitate the development of image dehazing techniques (see Fig. 10).

Recommendations

Recommendations for developers and researchers:
- Conduct further studies on single-image defogging algorithms under different foggy weather conditions.
- Consider retaining the details and achieving edge smoothing of dehazed images.
- Develop an algorithm that can recover the large areas of the sky and white objects.
- Balance the haze removal level and natural appearance in dehazed images.
- Reduce the complexity of haze removal methods.
- Focus on finding useful features, such as texture and structure.
- Use deeper neural networks when learning atmospheric scattering models.
- Decrease the number of classifier iterations.
- Integrate image fusion and enhancement approaches into the physical model.
- Minimize the filtering steps and avoid user interaction to achieve real-time requirements.
- Propose high-quality, assessment indexes and methods.
- Develop quality metrics that effectively correlate with the perceptual results on the basis of comprehensive scientific criteria.
- Provide a benchmarked image dataset.
- Consider different factors, such as number and quality of the test images, in the new dataset.
- Use an algorithm that can be ported on mobile devices.

Fig. 10. Image dehazing recommendation categories.

1. Recommendations of Developers and Researchers

a) Image Dehazing Methods

Conducting further studies on single-image defogging algorithms that can adaptively enhance foggy images acquired under different foggy weather conditions [6], [46], [64], such as night, dense, and inhomogeneous foggy weather; night conditions [74], sandstorms [50], effects of shadow, and unwanted light [126], is recommended. Several proposed algorithms suffer from various post-processing effects, such as dimness at the edges of dehazed images; thus, preserving the details, achieving edge smoothing for dehazed images [86], and performing additional improvements on existing dehazing methods in the future are recommended [116]. Notably, several methods fail to recover the large areas of the sky and white objects [153], [154] of degraded images. Thus, considering these issues when developing a particular method is important. Moreover, future dehazing algorithms must possess a balance between the natural appearance and the effects of the dehazing process for a specific image [36], [64].

In some existing defogging algorithms, parameters need to be manually set. Although an excellent performance can be obtained by constantly adjusting parameters, the result is unrealistic in real-time applications [6]. At present, most video dehazing processes are improvements of single image dehazing methods and usually contain complex data processing algorithms. These complex operations often require a long processing time [8]. However, most existing image dehazing algorithms have high time and space complexity. Most desirable scenarios in real-time applications provide an automatic and adaptive processing for needed images. Thus, reducing the complexity of haze removal methods [64], constantly adjusting performance parameters [6] or minimum user interaction [62], and concurrently processing a large number of videos such that atmospheric light estimation can be shared and coordinated between different videos [123], are recommended.

Emphasizing the search for beneficial features, such as texture and structure [125], and recovering degraded images from as few features as possible are recommended to establish a highly powerful neural network model for single-image dehazing [22]. Moreover, using deeper neural networks in the learning of atmospheric scattering models is suggested; in this case, an end-to-end mapping between hazy and haze-free images can be directly optimized without any need for estimation of medium transmission [68]. The number of classifier iterations should be minimized as much as possible to obtain the final result [32].

Apart from the widely used atmospheric scattering model, degradation models, such as the dual-color atmospheric scattering and atmospheric transfer function, are currently available. However, none of these models can accurately describe the phenomenon of haze degradation. Therefore, exploring some cues that have been obtained from research results of modern atmospheric optics (study of comprehensive degradation models), is necessary [8].

Many image enhancement methods have been developed on the basis of the human vision system. These methods can rapidly and accurately estimate image brightness and maintain true color. Image fusion methods can determine or obtain effective information from different source images. Thus, integrating image fusion and enhancement approaches into physical models is recommended [8].

All existing video defogging algorithms focus on surveillance scenes. No effective video defogging algorithm for a scene with a moving camera is available. The color shift problem also needs to be overcome in further studies [6]. Evidently, de-weathering based on multiple images and user interaction is unsuitable for driver assistance systems. A fully automated system is highly recommended for real-time image dehazing scenarios [62]. Furthermore, some algorithms have been recommended in the implementation of particular real-time applications [5], [66], [69], [87], [90], [93], [100], [112], [131], [124].

b) Image Quality Assessment

Given that previous objective assessment results are evidently inconsistent with subjective ones, directly applying them to evaluate different defogging algorithms is difficult because they are unable to make reliable judgments [6], [64]. Thus, an effective quality assessment index or method also needs to be proposed [6], [24]. At present, research on the quality assessment of dehazed images still requires further development, and the evaluation indexes are mainly concentrated on image clarity, contrast, color, and structural information and lack comprehensive scientific criteria. Thus, designing a special image quality assessment mechanism is necessary [8]. Furthermore, substantial work should be conducted to develop quality metrics that effectively correlate with perceptual results [35],[44]. The study recommends that the statistics of natural scenes in addition to the distortion of particular features be combined to generate a highly delicate objective image quality assessment method in the future [36].

c) Dataset Recommendations

Developers and researchers, such as [43], [44], [46], [55] recommend using several datasets to develop new fog removal algorithms and image quality assessment methods. However, the additional noise is a critical issue in the dehazing process and image quality assessment. Moreover, the noise in common datasets utilized for image quality assessment is artificially added. These datasets are unable to precisely reflect the real complex noise in normal hazy images. Therefore, creating a public benchmark dataset is recommended for image dehazing [22]. Furthermore, different factors, such as increasing the number and quality of test images, should be considered in new datasets [35], and hazy image datasets should include large bright regions that usually exist in natural scenes [32].

d) Cost Efficient Solution

According to [72], [73], enhancement algorithms can work in real-time environments, such as the pre-processing stages for several real life applications (e.g., traffic surveillance systems, basic image dehazing, and driving assistance systems). Additionally, these algorithms can be implemented on mobile devices. Thus, developers recommend using the aforementioned algorithms to support users with minimal cost and efficient solution for image visibility restoration in various driving scenarios.

VI. Limitations

The number and identity of the source databases are eminent limitations in our study because the process of searching related articles was based on three search engines of online databases. Nevertheless, the designated databases are reliable and provide relevant articles. In addition, the rapid development in the area affected the timeline of this survey. According to the time limitation, relevant studies do not necessarily cover the entire picture about trends, development, and effects of this area. Consequently, our study barely illustrates the number of responses from the image dehazing community to the area, which is the main target of this study.

VII. Conclusion

In the past decades, researchers have drawn notable attention to the image dehazing development, thereby making the image dehazing technology one of the major research topics. In this context, no clear boundaries have been observed in the development of this field. Thus, further study is necessary to provide a holistic view and track this research line. Our study attempts to provide an extensive view and deep understanding by reviewing and classifying the highly pertinent literature. Consequently, this study maps the final set of relevant articles in three main categories, namely, studies conducted on image dehazing, reviews and surveys, and real-time scenario-based development. Apart from providing an intensive investigation into the existing literature, the three main classes are divided into subcategories, such as comparative study, various types of evaluation methods, datasets, review articles conducted in general or supported specific scenarios, and evaluation criteria types that have been used to measure the efficiency of certain algorithms. In addition, further details, such as the challenges and obstacles in the image dehazing community, the relevant motivations behind holding a particular image dehazing study, notable recommendations stated by other researchers to mitigate existing hindrances, and various datasets that have been used to support evaluation methodologies and algorithm development processes, are presented through intensive search and analysis of the final set of articles in distinct forms. On the one hand, researchers have paid great attention to the development of real-time image dehazing algorithms. On the other hand, the existing literature reveals little concern about improving the evaluation procedure for certain image dehazing algorithms and handling related issues. Thus, the image dehazing community should exert substantial efforts toward the development of new evaluation methodologies and resolving the obstacles in the evaluation process. Finally, our systematic review will help researchers track the critical issues regarding image dehazing, thereby extending and drawing further research directions.

Appendix

Appendix A. Dataset Statistics

Ref	Dataset	Over-land	Over-water	Underwater	real	Synthesis	Indoor	Outdoor	Source
[55]	30 images based on five scenes	×	×	✓	×	×	×	×	[55]
[44]	CHIC (Color Hazy Image For Comparison) dataset = 9 images (publicly available)	✓	×	×	×	✓	✓	×	http://chic.u-bourgogne.fr
[48]	More than 3464 images	✓	×	×	✓	×	×	✓	[48]
[47]	SAMEER-TU Database = 5390 images	✓	×	×	✓	×	×	✓	[47]
[45]	D-HAZY dataset = 1400+ pairs of images	✓	×	×	×	✓	✓	×	[45]
[43]	Large-volume road scene dataset = 2000 images	✓	×	×	×	✓	×	×	[43]
[40]	Underwater dataset = 87 images	×	×	✓	×	✓	×	×	[40]
[87]	100 images	✓	×	×	✓	×	×	✓	[87]
[68]	12 pairs of stereo images collected from the Middlebury Stereo Datasets (publicly available)	✓	×	×	×	✓	✓	×	http://vision.middlebury.edu/stereo/data/
[97]	Two weather degraded videos, namely, “Riverside” and “Road View” (publicly available)	✓	×	×	✓	×	×	✓	http://mcl.korea.ac.kr/projects/dehazing/

Ref	Dataset	Over-land	Over-water	Underwater	real	Synthesis	Indoor	Outdoor	Source
[96]	IV-M dataset = 24 images	✓	×	×	✓	×	×	✓	[96]
[155]	Multiple real-world foggy image dataset (MRFID)= 200 clear images and each with four Corresponding foggy images of different densities. DMRFIs= 12,800 defogged images	✓	×	×	✓	×	×	✓	http://www.vistalab.ac.cn/MRFID-for-defoggin
[156]	Synthetic haze removing quality (SHRQ) database=675	✓	×	×	×	✓	✓	✓	[156]
[157]	22 ✓airs of hazy images and haze-free images (ground truth)	✓	×	×	×	✓	✓	×	[157]
[25]	REalistic Single-Image DEhazing (RESIDE)= 13, 990 synthetic hazy	✓	×	×	×	✓	✓	✓	https://sites.google.com/view/reside-dehaze-datasets/reside-standard?authuser=0
[158]	Overall dehazing quality (DHQ)=1,750 images	✓	×	×	✓	×	×	✓	[158]
[159]	Non-homogeneous realistic dataset NH-HAZE= 55 scenes	✓	×	×	×	✓	×	✓	https://data.vision.ee.ethz.ch/cvl/ntire20/nh-haze/
[160]	Vehicles Small Object Dataset (VSOD)	✓	×	×	×	✓	×	✓	[160]
[161]	Dense-Haze dataset =33 pairs of images	✓	×	×	×	✓	×	✓	[161]
[162]	More than 1000	✓	×	×	✓	×	✓	✓	[162]
[163]	Visibility Range Haze Simulation(VRHAZE) =8 pairs images	✓	×	×	×	✓	×	✓	[163]
[164]	57 image pairs	×	×	✓	✓	×	×	×	http://csms.haifa.ac.il/profiles/tTreibitz/datasets/ambient_forwardlooking/index.html
[165]	U45= 45 images	×	×	✓	✓	×	×	×	https://github.com/IPNUISTlegal/underwater-test-dataset-U45-
[166]	Underwater Image Enhancement Benchmark (UIEB) =950 images	×	×	✓	✓	×	×	×	https://li-chongyi.github.io/proj_benchmark.html
[167]	Over-wate Haze=4531 images	×	✓	×	✓	×	×	✓	[167]
[168]	I-HAZE= 35 image pairs	✓	×	×	×	✓	✓	×	[168]
[169]	O-HAZE= 45 image pairs	✓	×	×	×	✓	×	✓	https://data.vision.ee.ethz.ch/cvl/ntire18//o-haze/
[170]	20550 images	✓	×	×	×	✓	×	✓	[170]
[171]	CHIC (Color Hazy Images for Comparison) = two indoor and two outdoor scenes	✓	×	×	×	✓	✓	×	http://chic.u-bourgogne.fr/
[172]	LIVE Image Defogging Database=1100 images	✓	×	×	✓	×	×	✓	https://live.ece.utexas.edu/research/fog/fade_defade.html

Appendix B. Critical Analysis of Real-time Image Dehazing Algorithms

	Approach					Evaluation		Data type				
Ref	Image restoration	Image enhancement	Image fusion	Hybrid	Technique	Subjective	Objective	Image	video	Image and video	Scene type	Application support
[173]	×	×	×	✓	Multi-band decomposition	✓	✓	✓	×	×	General	Robot Vision
[174]	✓	×	×	×	CONVEX OPTIMIZATION	×	✓	✓	×	×	General	Not specified
[175]	✓	×	×	×	Boundary Constraint and Contextual Regularization	×	✓	✓	×	×	General	Not specified
[176]	×	×	×	✓	open dark channel and Wavelet	×	✓	✓	×	×	General	Not specified
[177]	✓	×	×	×	non-local prior	✓	✓	✓	×	×	General	Not specified
[178]	×	×	×	✓	Bilateral Filter	✓	×	✓	×	×	General	Not specified
[179]	×	×	×	✓	White Balance and image decomposition	✓	✓	✓	×	×	General	Not specified
[180]	×	✓	×	×	Guided Image Filtering	×	✓	✓	×	×	General	Not specified
[181]	×	✓	×	×	Guided joint bilateral filter	×	✓	×	×	✓	General	Not specified
[182]	✓	×	×	×	linear combination of the direct transmission, airlight and glow	×	✓	✓	×	×	Night-time	Not specified
[183]	×	✓	×	×	median filter	✓	✓	✓	×	×	General	lane-marking and obstacle detection
[112]	✓	×	×	×	DCP and GIR filter	×	✓	✓	×	×	General	Not specified
[50]	✓	×	×	×	HSV color space	×	✓	✓	×	×	General	Not specified
[71]	✓	×	×	×	DCP	×	✓	×	×	✓	General	Driver assistance system
[77]	✓	×	×	×	DCP	×	✓	×	✓	×	General	Power station monitoring
[78]	✓	×	×	×	Locally adaptive Wiener defogging	×	✓	×	✓	×	General	Optical system for observing targets
[87]	×	×	×	✓	Fusion weighting scheme and atmospheric light	✓	✓	×	×	✓	General	Not specified
[93]	✓	×	×	×	DCP	×	✓	✓	×	×	General	Not specified
[100]	×	×	×	✓	Retinex based and DCP	×	✓	✓	×	×	General	Not specified
[79]	×	✓	×	×	CLAHE	×	✓	×	✓	×	General	Real-time video surveillance system
[74]	×	✓	×	×	Histogram equalization	×	✓	✓	×	×	General	Road edge detection and road obstacle detection
[98]	×	×	✓	×	Per-pixel strategy	×	✓	✓	×	×	General	Not specified
[88]	✓	×	×	×	Boundary constraints and bilateral filtering	×	✓	×	×	✓	General	Not specified
[72]	✓	×	×	×	New mathematical model	×	✓	✓	×	×	General	Driver assistance system
[73]	✓	×	×	×	New mathematical model	×	✓	✓	×	×	Daytime	Driver assistance system
[90]	✓	×	×	×	DCP and median DCP (MDCP)	×	✓	×	✓	×	General	Not specified
[75]	✓	×	×	×	DCP	×	✓	✓	×	×	General	Road marking feature extraction and road sign detection

Ref	Approach				Technique	Evaluation		Data type			Scene type	Application support
	Image restoration	Image enhancement	Image fusion	Hybrid		Subjective	Objective	Image	video	Image and video		
[94]	✓	×	×	×	Bilateral and DCP guided filters	×	✓	✓	×	×	General	Not specified
[116]	✓	×	×	×	Linear transformation	×	✓	✓	×	×	General	Not specified
[154]	×	×	×	✓	Joint LLSURE	×	✓	✓	×	×	General	Not specified
[97]	×	✓	×	×	Gamma correction	×	✓	×	×	✓	General	Not specified
[56]	✓	×	×	×	DCP (guided filter)	×	✓	✓	×	×	General	Not specified
[95]	✓	×	×	×	DCP and bilateral filters	✓	✓	✓	×	×	General	Not specified
[81]	✓	×	×	×	DCP	×	✓	✓	×	×	General	embedded systems
[82]	✓	×	×	×	DCP	×	✓	×	×	✓	General	Unmanned aerial vehicle (UAV)
[134]	✓	×	×	×	HRNFP	×	✓	✓	×	×	General	Not specified
[150]	✓	×	×	×	DCP	×	✓	✓	×	×	Sky	Not specified
[91]	×	×	×	✓	DCP and multi-scale retinex	×	✓	✓	×	×	General	Not specified
[83]	✓	×	×	×	MDCP	×	✓	✓	×	×	General	Car vision systems
[84]	✓	×	×	×	CABFD	×	✓	✓	×	×	General	Not specified
[76]	✓	×	×	×	Flat-world assumption	×	✓	✓	×	×	Daytime	Road marking, road sign, and road obstacle detection
[184]	✓	×	×	×	DCP and fast Fourier transform	×	✓	✓	×	×	General	Not specified
[102]	×	×	×	✓	DCP and infrared-blue light intensity difference factor	×	✓	✓	×	×	General	Mobile cloud of smart city
[96]	✓	×	×	×	DCP	✓	✓	✓	×	×	Sky	Not specified
[128]	✓	×	×	×	Adaptive DCP	×	✓	✓	×	×	Sky	Not specified
[101]	×	×	×	✓	Digital total variation (TV) filter with color transfer (DTVFCT)	×	✓	✓	×	×	General	Not specified
[105]	✓	×	×	×	Machine learning	×	✓	✓	×	×	General	Not specified
[99]	×	×	✓	×	White balance and a contrast enhancing procedure	×	✓	✓	×	×	General	Not specified
[57]	✓	×	×	×	Color ellipsoid prior	×	✓	✓	×	×	General	Not specified
[103]	×	×	×	✓	DCP and reliability guided fusion	×	✓	✓	×	×	General	Not specified
[89]	✓	×	×	×	Mean filter (DCP)	×	✓	×	×	✓	Sky	Not specified
[92]	✓	×	×	×	Joint trigonometric filter	×	✓	✓	×	×	General	Not specified
[80]	×	×	×	✓	DCP and multiscale retinex	×	✓	×	✓	×	General	Surveillance camera system
[106]	✓	×	×	×	Machine learning	×	✓	✓	×	×	General	Not specified
[104]	✓	×	×	×	DCP and histogram-based S-shaped transfer mapping	×	✓	✓	×	×	General	Not specified
[85]	✓	×	×	×	DCP	×	✓	×	×	✓	General	Not specified
[185]	×	✓	×	×	gamma-correction operations	✓	✓	✓	×	×	General	Not specified

	Approach					Evaluation		Data type				
Ref	Image restoration	Image enhancement	Image fusion	Hybrid	Technique	Subjective	Objective	Image	video	Image and video	Scene type	Application support
[186]	✓	×	×	×	DCP	×	✓	✓	×	×	General	Agriculture
[187]	×	×	×	✓	local Laplacian filtering and DCP	✓	✓	✓	×	×	Sky	Not specified
[188]	✓	×	×	×	Fusion of Luminance and Dark Channel Prior (F-LDCP)	×	✓	✓	×	×	Sky	Not specified
[189]	✓	×	×	×	simple radiographic scattering model	×	✓	✓	×	×	x-ray industrial objects	nondestructive testing (NDT)
[190]	×	✓	×	×	multi-scale retinex	×	✓	✓	×	×	General	Not specified
[191]	✓	×	×	×	Retinex and DCP	✓	✓	✓	×	×	Dark	Not specified
[192]	✓	×	×	×	Machine learning	✓	✓	✓	×	×	General	Not specified
[193]	✓	×	×	×	image decomposition	✓	✓	✓	×	×	Dark	Not specified
[194]	✓	×	×	×	Machine learning	✓	✓	✓	×	×	General	Not specified
[195]	✓	×	×	×	Machine learning	×	✓	✓	×	×	Sky	railway industry
[196]	✓	×	×	×	DCP	×	×	✓	×	×	General	Steganography
[197]	✓	×	×	×	Machine learning	✓	✓	✓	×	×	General	UAV-based railway
[198]	✓	×	×	×	Machine learning	×	✓	✓	×	×	Inhomogeneous	Not specified
[199]	✓	×	×	×	DCP	✓	✓	✓	×	×	General	Not specified
[200]	✓	×	×	×	Machine learning	×	✓	✓	×	×	General	Not specified
[201]	✓	×	×	×	DCP	×	✓	×	×	✓	General	Measurement of vehicle safe distance
[202]	✓	×	×	×	n/a	×	×	✓	×	×	n/a	Biometric
[203]	✓	×	×	×	Machine learning	✓	✓	×	×	✓	General	Safe Autonomous Driving
[204]	×	✓	×	×	Retinex	✓	✓	✓	×	×	General	Not specified
[205]	✓	×	×	×	haze-line	×	×	✓	×	×	n/a	TV industry
[206]	✓	×	×	×	DCP	×	✓	✓	×	×	General	Agriculture
[207]	✓	×	×	×	Machine learning	×	✓	✓	×	×	Sky	Not specified

Appendix C. Evaluation Results Based on Homogeneous Foggy Scene (Live)

Algorithm	e	r	Σ	HCC	SSIM	UQI	Time
Dehazenet	4.1588	1.4960	0.0001	0.0413	0.8602	0.8410	2.5464
MSCNN	4.1538	1.5652	0.0003	0.088498	0.860096	0.8794	1.8726
Colores	8.0088	1.6923	0.0009	-0.2389	0.758971	0.723296	2.243798
Zhu	5.5400	1.5027	0.00001	-0.0139	0.847028	0.829924	2.298305
Multi-band	15.0721	2.9541	0.0005	-0.2509	**0.576338**	0.703543	0.836256
CODHWT	2.989583	1.361311	0.000051	**0.424145**	0.936578	0.934878	1.809423
Meng	10.23	2.295751	0.005086	-0.327609	0.636078	0.674045	4.793871
Liu	6.318333	1.744583	0.00019	-0.379144	0.638409	0.584564	0.962875
Berman	6.968333	2.349564	0.001553	-0.145496	0.68528	0.760354	9.383139
BF	1.7842	1.7492	0.0239	0.1573	0.8527	0.9689	5.2163
WBCID	0.029583	1.178055	0.0000	-0.3773	0.5656	**0.5791**	**0.6679**
GF	-3.0704	1.8864	0.0526	0.1330	0.7693	0.9714	2.8796
JBF	1.6775	1.6466	0.0123	0.1661	0.8813	0.9608	3.3174
Kim	3.6721	1.5126	0.0000	0.0145	0.8291	0.8417	1.6261
NHR	**14.2233**	**4.0722**	0.0142	0.1540	0.5631	0.9199	32.3782
He et al.	-0.7771	1.5615	0.0247	0.2261	0.8820	0.9835	20.4726
Tarel	12.9742	2.0086	**0.0000**	0.4122	0.8452	0.9618	4.4537

Appendix D. Evaluation Results Based on Dark Foggy Scene (Live)

Algorithm	e	r	Σ	HCC	SSIM	UQI	Time
Dehazenet	19.9871	1.3402	0.0128	-0.276955	0.658398	0.4827	3.2670
MSCNN	7.0346	1.1566	0.0008	0.539402	0.9625	0.938295	2.7783
Colores	14.1258	1.7970	0.0024	0.6412	0.8554	0.904098	2.1217
Zhu	16.705	1.2442	0.0004	-0.184528	0.7691	0.624096	2.3334
Multiband	23.0579	3.3220	0.0228	0.0120	0.5338	0.702196	1.8406
CODHWT	9.465	1.258896	0.001844	0.298458	0.883852	0.818569	1.971623
Meng	25.232083	3.178712	0.016137	-0.127894	0.577913	0.7351	4.841839
Liu	17.58625	1.945983	0.008957	-0.24152	0.603954	**0.555025**	0.852609
Berman	20.094583	3.06916	0.027333	-0.098533	**0.519443**	0.590679	7.147162
BF	10.8713	1.5772	0.0024	0.794161	0.916754	0.9769	5.2852
WBCID	3.6238	1.0175	0.0015	0.123286	0.846532	0.8484	**0.6304**
GF	9.8704	1.4801	0.0015	0.765783	0.930932	0.9742	3.8447
JBF	10.2158	1.5321	0.0018	**0.798623**	0.92159	0.9766	3.0011
Kim	15.129583	1.1581	**0.0000**	-0.081301	0.812525	0.7123	1.7037
NHR	26.8883	**4.8943**	0.0152	0.353259	0.480202	0.9024	33.3985
He et al.	11.6904	1.5489	0.0016	0.7082	0.915269	0.9625	18.6767
Tarel	**27.8892**	2.4675	**0.0000**	0.249464	0.779644	0.8962	4.4015

Appendix E. Evaluation Results Based on Sky Foggy Scene (Live)

Algorithm	e	r	Σ	HCC	SSIM	UQI	Time
Dehazenet	4.7113	0.9589	0.0043	0.307916	0.936388	0.9025	2.6442
MSCNN	5.7746	1.0628	0.0008	0.213925	0.9187	0.902131	1.9396
Colores	5.8375	1.1903	0.0003	-0.0806	0.9206	0.931895	2.6293
Zhu	4.080417	0.9243	**0.0000**	**0.334325**	0.9682	0.974045	2.2935
Multiband	7.3025	2.3827	0.0020	0.2544	0.7084	0.85643	0.8098
CODHWT	4.11625	0.840657	**0.0000**	0.315035	0.928537	0.891593	1.613
Meng	15.6625	1.801919	0.000208	0.080183	0.83313	0.884057	4.325442
Liu	6.89375	1.286005	0.00025	0.109946	0.779111	0.740609	0.857336
Berman	9.845417	1.771679	0.005214	0.017815	0.767244	0.843084	10.199034
BF	-10.2125	1.0394	0.2444	-0.054068	0.713872	0.8511	5.4393
WBCID	-6.2750	0.5114	**0.0000**	0.085668	0.680668	0.8851	**0.6714**
GF	-7.2796	1.7923	0.2456	-0.056397	**0.630068**	**0.8385**	3.3170
JBF	-5.0350	1.7363	0.2176	-0.056235	0.671786	0.8619	3.3787
Kim	3.1346	0.9974	**0.0000**	0.140081	0.936219	0.9598	1.6741
NHR	6.3183	**2.7691**	0.1241	-0.047596	0.688985	0.9293	25.5386
He et al.	4.3975	1.0602	0.0411	-0.038059	0.956283	0.9809	18.7453
Tarel	**11.0075**	1.7998	**0.0000**	0.115319	0.798529	0.8601	5.3438

Appendix F. Evaluation Results Based on Inhomogeneous Foggy Scene (RESIDE)

Algorithm	e	r	Σ	HCC	SSIM	UQI	Time
Dehazenet	7.935049	0.854451	0.0185	0.1359	0.7425	0.6672	2.3510
MSCNN	9.297229	1.0999	0.0079	0.3668	0.8215	0.7970	1.5016
Colores	7.416572	1.3486	0.0012	0.3577	0.8951	0.9400	2.4097
Zhu	1.9523	1.1116	0.0001	**0.5563**	0.8819	0.9077	1.5011
Multiband	22.276112	2.4266	0.0100	0.2261	**0.6016**	0.7249	0.8679
CODHWT	7.989725	0.863739	0.00167	0.22102	0.753898	0.695235	1.310947
Meng	15.409125	1.823188	0.02838	-0.109583	0.763196	0.794093	4.727146
Liu	13.722191	1.501098	0.003609	0.021543	0.65972	0.60865	0.866733
Berman	20.383201	1.976998	0.026848	-0.071128	0.511494	**0.558347**	3.451106
BF	10.460973	1.49539	0.0132	0.0101	0.8345	0.8679	5.1954
WBCID	-4.245852	0.605494	**0.0000**	0.2434	0.6810	0.8055	**0.5932**
GF	5.001414	1.158141	0.0203	-0.0101	0.8522	0.8806	4.0565
JBF	3.49736	1.015395	**0.0000**	0.3248	0.8468	0.8591	3.7495
Kim	-0.776772	1.249675	0.0002	0.4708	0.9155	0.9757	1.8187
NHR	**25.607089**	**4.095499**	0.0234	-0.1204	0.5311	0.8973	15.5492
He et al.	3.565705	1.258651	0.0032	0.2087	0.9067	0.9587	18.0359
Tarel	19.536199	3.357711	0.0002	0.4999	0.6243	0.8480	3.6023

Appendix G. Evaluation Results Based on Homogeneous Foggy Scene (RESIDE)

Algorithm	e	r	Σ	HCC	SSIM	UQI	Time
Dehazenet	3.5388	1.9113	**0.0000**	0.7258	0.9314	0.9787	2.3979
MSCNN	9.1789	2.8502	**0.0000**	0.814069	0.868812	0.9589	1.8033
Colores	12.5962	4.0872	0.0034	0.2654	0.718492	0.88795	2.38427
Zhu	2.6065	1.7850	**0.00000**	0.7580	0.941935	0.984282	2.212608
Multiband	13.9621	4.8493	**0.0000**	0.7529	0.738212	0.910496	0.848164
CODHWT	1.014329	1.418885	0	**0.939925**	0.971873	0.99807	1.2825
Meng	32.944476	8.405718	0.012264	-0.086677	**0.541719**	0.837048	3.809055
Liu	16.002074	5.159446	0.000105	0.398135	0.675243	0.908446	0.821688
Berman	24.737462	6.874965	0.00005	0.279624	0.576514	0.860761	3.001658
BF	7.4618	2.5616	**0.0000**	0.5586	0.8851	0.9829	4.6799
WBCID	3.3211	2.2371	**0.0000**	0.3524	0.8625	0.9354	**0.5807**
GF	5.7669	3.1820	0.2470	-0.0186	0.8835	0.9291	3.8348
JBF	6.6431	3.0093	0.1427	-0.0065	0.8715	0.9519	4.1577
Kim	9.2671	3.2265	**0.0000**	0.4194	0.8546	0.9577	1.4141
NHR	**47.6654**	**9.1384**	0.0004	-0.2394	0.3228	**0.4333**	34.7232
He et al.	5.6439	2.8043	0.1636	-0.0118	0.8850	0.9471	18.1905
Tarel	11.8085	3.7466	**0.0000**	0.0246	0.7963	0.9581	3.5908

Appendix H. Evaluation Results Based on Dark Foggy Scene (RESIDE)

Algorithm	e	r	Σ	HCC	SSIM	UQI	Time
Dehazenet	6.7713	1.0578	0.0160	0.404655	0.860955	0.7891	2.4317
MSCNN	6.7944	0.9424	0.0096	0.145465	**0.8040**	0.671941	1.7006
Colores	6.8755	1.1209	0.0004	0.5106	0.9387	0.869402	3.3024
Zhu	2.884615	0.9944	**0.0000**	**0.993043**	0.9801	0.985353	1.4978
Multiband	23.9621	**3.0297**	0.0009	0.6262	0.8405	0.914939	**0.6546**
CODHWT	2.631976	0.999548	0.00003	0.139021	0.934012	0.876721	1.307001
Meng	7.511312	1.671939	0.000184	0.71885	0.861989	0.88257	4.816429
Liu	4.564951	0.963581	0.000069	0.459224	0.950932	0.87996	0.813935
Berman	3.300339	1.168217	0.00231	0.65091	0.955972	0.932679	10.36607
BF	4.7125	1.0423	0.0001	0.848326	0.976514	0.9573	4.8856
WBCID	-1.2967	0.7573	**0.0000**	0.622145	0.968764	0.9672	0.6671
GF	3.4106	0.9641	0.0001	0.865405	0.976906	0.9589	3.1854
JBF	3.3965	0.9655	0.0001	0.865081	0.976817	0.9588	4.0713
Kim	5.5543	1.0219	0.0001	0.97595	0.969048	0.9259	1.4256
NHR	**32.2643**	1.5287	0.0034	0.509224	0.565946	**0.4016**	16.3898
He et al.	4.3670	1.0412	0.0005	0.960589	0.981552	0.9745	17.3223
Tarel	8.6732	1.3766	**0.0000**	0.333919	0.931369	0.9044	3.5156

Appendix I. Evaluation Results Based on Sky Foggy Scene (RESIDE)

Algorithm	e	r	Σ	HCC	SSIM	UQI	Time
Dehazenet	4.5692	0.9386	0.0048	0.246052	0.784905	0.7265	2.2933
MSCNN	9.1987	1.3668	**0.0000**	0.305573	0.8480	0.886879	1.6186
Colores	6.5031	1.2967	0.0002	0.0367	0.8445	0.847032	2.1885
Zhu	1.657711	0.9709	**0.0000**	0.293672	0.8594	0.87639	2.2368
Multiband	21.6893	3.1120	0.0006	-0.1611	0.5866	0.742517	0.8356
CODHWT	4.471625	1.032288	0.00154	0.358459	0.816675	0.786138	1.31625
Meng	9.467383	1.862447	0.029514	-0.16236	0.80443	0.884386	4.338396
Liu et al.	18.289498	1.617126	0.000814	-0.464062	0.547117	**0.489511**	0.818556
Berman	20.034408	2.400936	0.00219	-0.232462	0.614909	0.680839	9.437322
BF	-0.6820	1.3640	0.1588	-0.090832	0.85684	0.9283	5.5421
WBCID	8.5831	1.1935	0.0002	-0.241839	**0.486279**	0.6201	**0.6067**
GF	1.8010	1.4817	0.1355	-0.089848	0.858631	0.9431	3.1114
JBF	7.6574	4.0109	0.1737	-0.108979	0.638098	0.8393	3.2164
Kim	3.2589	1.2584	**0.0000**	**0.451376**	0.882397	0.9451	1.4026
NHR	**24.2605**	**4.8230**	0.0105	-0.080688	0.534496	0.9346	24.2869
He et al.	2.9044	1.1994	0.0505	-0.089424	0.888942	0.9503	17.5200
Tarel	19.7459	2.8175	**0.0000**	0.299531	0.695741	0.8827	4.2647

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