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Review

Fog Water: A General Review of Its Physical and Chemical Aspects

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Abstract: Studies concerning fog water have been rapidly increasing due to its negative impacts on different environmental processes. However, fog water harvesting has become beneficial in various countries to overcome water scarcity. Accurate fog forecasting remains a challenging issue due to its spatio-temporal variability and uncertainties despite the development and efforts made to understand its chemistry and microphysics. The literature proved that the decrease in fog frequency over time in most countries is mainly attributed to the improvement in air quality or the change in regional climatic conditions. The current fog review summarizes its different types and collectors, life cycle, and impacts, the effects of aerosols, and the latest results concerning its forecast challenges and frequency. It also highlights the major chemical processes along with the main field studies performed on fog water. The aim of this work is not to provide a criticism about fog but to present a general comprehensive review of its physical and chemical aspects covering up to 330 research and review papers aimed to serve as a basis for new challenges and findings about fog water.

Keywords: fog impacts; fog lifecyle; fog collectors; fog forecasting; fog frequency; fog observations

Citation: Khoury, D.; Millet, M.; Jabali, Y.; Delhomme, O. Fog Water: A General Review of Its Physical and Chemical Aspects. *Environments* **2023**, *10*, 224. https://doi.org/10.3390/environments10120224

Academic Editor: Peiyue Li

Received: 14 November 2023
Revised: 11 December 2023
Accepted: 15 December 2023
Published: 18 December 2023

1. Introduction

Atmospheric pollution, characterized by measurements of biological, physical, or chemical contaminants, has become an international policy problem having harmful consequences for human health and ecosystems [1,2]. Accordingly, fog droplets are composed of a mixture of organic and inorganic compounds resulting from scavenging hygroscopic particles and water-soluble trace gases. Fog droplets are formed on aerosol particles in a supersaturated atmosphere. However, the pollution loadings of these particles are higher than those in clouds and precipitation [3]. It is the result of the synergic effect of weather factors (relative humidity (RH), wind direction (WD), wind velocity (WS), temperature (T), pressure (P), etc.) and pollution (presence of aerosols) [4]. Its chemical composition is an important tool for the complementary analysis and identification of air and long-range transport (LRT) pollutants because fog is formed in a shallow boundary layer which is conducive to fog formation and has the ability to trap local and regional pollutants. According to the American Meteorological Society (AMS), fog comprises a large number of small water droplets in the liquid form or ice crystals suspended in the atmosphere reducing the visibility below 1 km (0.62 miles) in the surrounding area [5]. Surface visibility is critical for aviation, transportation, and land safety, causing significant human and financial losses, and is responsible for serious air, land, and water transportation [6–8]. Modern aircraft have no difficulties with fogs of 1 km, but some restrictions can be imposed when the visibility degrades to lower than that. Visibility of less than 500 m is classified as fog [9].

The reduction in visibility depends on the resulting distribution of fog droplets and on the concentration of cloud condensation nuclei (CCN). The densest and thickest fog mainly occurs in urban or industrialized areas in the presence of a high number of polluted particles in the air acting as CCN for water droplets [5,10]. Fog is of great meteorological significance due to its strong relation to humidity factors and its capability of reducing the temperature amplitude and local character of formation. Its formation, existence, and dissipation are strongly influenced by numerous factors including local orographic conditions (changes in atmospheric conditions), atmospheric circulations (heat distribution by large-scale air masses), and the actual synoptic situation (pressure pattern, fronts, wind direction, wind speed, etc.) [10]. The presence of natural fog affects many environmental components including global and local climate, air quality, water quality, air–surface interactions, the thermal and radiative budget of the atmosphere, etc. [11,12]. It has severe impacts on social life leading to an increase in the number of injuries due to the reduced visibility whether in water, air, or land transportation [5,12]. Fog has also direct and indirect adverse impacts on human beings (primary and secondary) [13]. However, it has a beneficial effect on decreasing the concentration of different air pollutants, cleaning the atmosphere through the wet deposition phenomenon, and agricultural and water supply activities [14,15]. Therefore, monitoring these climatic events in the different environmental matrices is crucial to better understand the consequences of their presence in the environment and to meet the criteria for defining good air quality. The assessment of major organic compounds in fog water is complex and has created much curiosity in sampling, analyzing, and elucidating the chemistry of fog water [14,16]. Lately, the knowledge of fog water chemistry has been widely expanded to include a wider number of pesticides, phenols, acids, polycyclic aromatic hydrocarbons, polychlorinated pesticides, and other organic families [16–19].

Fog droplets acquire their chemical composition by mechanisms similar to those of cloud water droplets [20]. The solute concentrations in fog water (organic acids, heavy metals, ions, etc.) are usually up to 100 times higher than those observed in precipitation due to the longer residence time in the atmosphere and their smaller droplet size. The longer residence time makes possible the higher accumulation of the products of the liquid-phase processes. The major composition of fog water is the result of the interaction of sulfur dioxide (SO_2), nitrogen oxide (NO_x), carbon dioxide (CO_2), hydrogen chloride (HCl), and ammonia (NH_3) with water in an oxidative atmosphere (oxygen (O_2), ozone (O_3), sunlight, etc.) and in the presence of trace metals that may act as redox catalysts (iron (Fe), copper (Cu), manganese (Mn), and organic materials including dust, soot, and hydrocarbons (HCs)) [21]. Fogs act as a micro-reactor for chemical and photochemical reactions with atmospheric oxidants such as singlet oxygen, hydroxyl radical, nitrate radical, etc. They are important media for aqueous-phase reactions where inorganic gases such as SO_2, NO_x, and dissolved volatile organic compounds (VOCs) are oxidized. These reactions accumulate the oxidized inorganic and organic matters in fog water and promote both the removal of particles from the atmosphere through wet deposition or the formation of new particles through oxidative reactions, aerosol formation, nucleation scavenging, droplet evaporation (post-fog), etc. [21–23]. For instance, some gases react to produce new species which are left behind (as aerosols) after the evaporation of fog droplets [3]. Some of the atmospheric pollutants, such as the secondary organic aerosols (SOAs) redisperse in the air after fog dissipation and provide nucleation seeds that will be more active acting as future CCN for the re-occurrence of other foggy events. Thus, fog is a multi-phase reservoir in which dry particulate matter (PM), gaseous components, and wet aerosols may coexist, and processes such as scavenging, aqueous-phase reactions, and nucleation occur simultaneously [22]. The contents of this review are structured as follows: In Section 2, the basic characteristics of fog types are described. In Section 3, fog forecasting is explored along with the elaboration of the different phases for radiation and valley fogs. In Section 4, fog frequency is summarized worldwide. In Section 5, fog droplet nucleation and activation processes along with the effect of aerosols and droplet size are explained. The negative and positive impacts of fog water on social life are detailed in Section 6,

followed by the description of some active and passive fog collectors in Section 7. Fog chemistry is elucidated in Section 8, showing the most important fog processes (oxidation, deposition, scavenging, and acid/base interaction). It also states the different field studies that have been performed all over the world. The basic conclusions of the review and some perspectives are summarized in Section 9.

2. Fog Types

Several points of view have been widely used in fog classification. It might be based on thermodynamic properties (mixed-phase fog), physical (freezing and ice fogs) and dynamical processes (turbulence and mixing fogs), the chemical composition of particles (dry fog), weather features (frontal fog), and the physiographic character of the surface (valley fog). Another point of view suggests that fog might be divided into three categories: liquid fog, mixed-phase fog, and ice fog. The latter forms when the temperature falls below −10 °C, liquid fog forms when the temperature is higher than −10 °C, and the mixed-phase fog forms between −10 °C and −30 °C [24]. However, fog might also form under special conditions. For instance, ice fog can occur at a temperature of −20 °C in the case of excessive vapor being absorbed by ice nuclei under steady-state conditions in the absence of mixing processes [11]. Willett proposes a fog classification based on favorable synoptic conditions. He sub-categorizes them into numerous types that might be formed in the atmosphere [25]. They include advection fog, valley fog, upslope fog, freezing fog, ice fog, steam fog, precipitation fog, and radiation fog [11,26–30]. Each type of fog is defined by a special physical process responsible for its formation [11]. Advection fog results in locations where warm air passes over cooler ocean water. As this process occurs, the temperature drops to the dew point, and water vapor condenses in the warm air, producing an RH of 100% and leading to the formation of fog. It mainly occurs in windy conditions such as on the Pacific coast of the US and San Francisco where the ocean is significantly cooler than the surrounding land. Typical fogs extend up to a few hundred meters in height [31]. Valley fog is formed during winter in mountain valleys where the dense air is trapped in the valley. In this area, the dense air settles down the valley and condenses to form fog. It is essentially due to a temperature inversion along with warmer air flowing above the valley. It may last for a few days during winter in calm conditions. Upslope fog occurs when the air flow rises up the terrain and cools it adiabatically to its saturation temperature allowing water vapor to condense to form fog. When it is seen from below, it is viewed as stratus clouds; as one goes up into the cloud, it is viewed as fog. This type is also known as the orographic fog. Freezing fog is formed when water droplets in the air mass become supercooled, and solid surfaces are frozen. As the fog intensity increases, the ground, trees, and other objects are glazed by a layer of rime or frost. Freezing foggy events occur at temperatures below 0 °C. Ice fog develops in Polar or Arctic regions where air temperature is below freezing. It is usually observed at high altitudes, in calm and clear weather, and in extremely cold air (<−29 °C). Ice fog is composed of ice crystals suspended in the air instead of supercooled water droplets. It results when water vapor is released into the atmosphere and is then condensed to form droplets that are rapidly frozen into ice particles. Steam fog is somehow the reverse of the advection fog. It occurs when cold air passes over relatively warm water. The air is cooled and moistened, causing the dew point to increase, causing condensation of water vapor leading to the formation of fog. It is a common phenomenon occurring during early winter and autumn, in middle latitudes, near rivers and lakes where water is still warm [32–34]. Precipitation fog is associated with weather fronts, especially warm frontal boundaries. It is formed when warm rain falls through cold and almost saturated air. When the precipitation falls down into colder air, the quantity of water vapor in the atmosphere is increased through evaporation, causing the dew point to rise and the cool air to become saturated to form fog. It is also known as frontal fog [31,35–38]. Radiation fog is known as ground or continental fog that does not reach any of the clouds overhead. It usually occurs at night under stable conditions (clear sky and calm wind) and dissipates in the morning as the ground warms by increasing the heating rate from thermal radiation. This

type is common in continental climates during winter under anticyclonic conditions (high pressure). Radiation fog is produced when the heat absorbed by the surface is radiated into the air, cooling the ground and causing a temperature inversion. As the surface cools, a layer of moist air is created near the ground and reaches its dew point. At this point, condensation occurs, resulting in the formation of fog [39]. The depth of the radiation fog increases as long as sufficient moist air is available. Typical ground fogs reach 100 to 200 m in height. Radiation fog is a mixture of liquid droplets, gaseous species, wet aerosols, and dry PM, resulting from complex interactions among these phases, contributing to the enrichment of fog droplets with inorganic and organic contaminations. Briefly, two basic concepts lead to fog formation: either air temperature reaches the dew point, forming advection, upslope, and radiation fog, or sufficient vapor is added to the air, forming frontal and evaporation fog [40].

3. Fog Forecasting

Fog is an important meteorological phenomenon that should be predicted accurately due to its strong influence on the economy and personal safety. Poor forecasting leads to a greater disruption to surface, sea, and air transport with subsequent increased risk to the economy and personal and social life. Fog is influenced by numerous factors, covering multiple temporal and spatial scales [11]. Fog formation is correlated with the presence of meteoroidal conditions such as low temperature, wind speed, wind direction, and very high relative humidity. In fact, fog does not always occur in windless and calm conditions. A historical dense foggy event was reported by Scott in 1896, stating that fogs with strong winds accompanied by heavy rain occurred in the British Isles. Fog-related events associated with strong winds are estimated to be about 135 in 15 years [41,42]. In 1892, fog formation was found to be related to the role of aerosols. Mensbrugghe states that "aqueous vapor condenses in the air only in the presence of solid particles around which the invisible vapor becomes a liquid" [43]. Additionally, Willett emphasizes the importance of CCN in fog formation. He reports that dust particles, hygroscopic particles, and those having an electric charge or ions facilitate fog formation [25]. The presence of hydrophilic particles is an important key that facilitates the condensation of water vapor into fog droplets. The pollution does lead to fog formation, and the heterogeneous nucleation of pollution condensation nuclei leads to fog droplet formation. The increasing quantity in polluted atmospheres decreases the surface tension, causing the pollution particles to be activated at lower relative humidity and resulting in a denser and thicker fog [44]. All these factors lead to the accumulation of pollutants in a stable and strong inversion boundary layer which is responsible for fog maintenance. Thus, air saturation with water vapor and favorable meteorological conditions are two driving parameters of fog formation. Fog appearance and dissipation are still not very clear since they are directly related to turbulence, microphysical and radiative processes, thermodynamics, and surface conditions. The reason behind that could be that fog is sensitive to the complex balance mechanism among all the processes. The initial conditions of turbulence and humidity are critical for the prediction of fog events. Some researchers suggest that fog is formed due to a turbulent mixing between nearly saturated eddies with slightly different temperatures when the colder air mixes and cools the hotter moister air reaching the saturation. Other researchers suggest that a virtual cessation of turbulence is necessary before fog formation. In this mechanism, it is assumed that the high levels of turbulence cause saturation to occur at the surface in the form of dew, preventing the coalescence of fog droplets and fog formation. Once formed, its further maturation or dissipation depends on the evolution of its physical processes and the environmental conditions that govern the removal and production of liquid water. Overall fog forecasting remains difficult and challenging since it depends on a large number of physical and chemical processes along with non-linear interactions. Factors that may be involved are many: atmospheric stability, radiation balance, moisture availability, turbulence, advection, topography, and microphysics [45]. Despite those limitations, it is important to work further on fog forecast to avoid its expected negative impact on social life and human health.

For this aim, researchers have used modeling that greatly ameliorates the ability to forecast severe events to some extent. Numerical weather prediction (NWP) models were first assessed by Ballard et al. to predict fog occurrence [46]. In that study, they employed the UK Meteorological Office mesoscale model implemented by Golding to predict a sea fog in the northeast Scottish coast [47]. They concluded that the accurate forecasting of fog primarily depends on the initial weather condition (relative humidity), physical parameters, sea surface temperature, and the treatment of synoptic forcing. In addition, models implemented by Zhou and Du and Van der Velde et al. are unable to forecast the accurate locations and life cycle of a fog layer [48,49]. Further simulations and models about the formation, vertical development, and dissipation of fogs are necessary to understand the physical mechanisms of fog layers [50,51]. Other researchers investigated the accuracy of fog prediction based on the vertical resolution [27,52,53], initial conditions [52], and horizontal resolution [54]. However, the NWP model for fog forecasting is still challenging and incomplete, since all studies did not take uncertainty into consideration regarding the visibility algorithms and complex processes in fog appearance, maturation, and dissipation [11,49,55–64]. Small errors in the initial state of the atmosphere contribute to unreliable fog forecasting [65–67]. Numerous studies investigated the performance of the NWP models and tried to operate such models for the prediction of fog between 12 and 72 h [68–72]. Despite the progress made for the NWP models in terms of physical parametrization schemes [58,73,74], land surface processes [54,65,75], and vertical and horizontal resolutions [59,62,76], the spatio-temporal variability of fog leads to a severe problem regarding the uncertainty attributed to individual model forecast which becomes impractical and useless after a certain time limit. Additionally, NWP presents some restrictions since its resolution is not enough, the stable boundary layer (SBL) is not well represented, the different microphysical processes are poorly considered, the systematic biases are difficult to overcome, the accurate data are difficult to initialize, and the variability conditions are needed to be kept up-to-date [45]. To overcome all the above-cited issues, the Ensemble Forecast System (EFS) is then employed for the probabilistic prediction of fog which takes into account the remaining uncertainty and some of the restrictions in the NWP model. The EFS model has proved its effectiveness in recent years in fog prediction in China, the US, and India [48,53,77]. Furthermore, some researchers have tried to use satellite data and imagery for fog prediction [78–87]. Satellite imagery has been an immense advantage in assessing weather hazards such as low clouds. The geostationary satellites that are employed by fog forecasters include the Geostationary Operational Environmental satellite (GOES) [88], Spinning Enhanced Visible and Infrared Imager System (SEVIRI) [78,79,85], Advanced Very-High Resolution Radiometer (AVHRR) [84,89,90], Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIOPSO) [91,92], Multifunctional Transport Satellite (MTSAT) [93,94], Moderate Resolution Imaging Spectroradiometer (MODIS) [80], and Indian National Satellite (INSAT-3D) [95–98]. In addition, some studies combined both numerical models with satellite data to fill gaps in the fog life cycle [56,99,100]. However, satellite-based fog detection still suffers from limited detection, since they do not consider all the available data obtained from satellite imagery. Therefore, numerous machine learning (ML) (decision tree, random forest, support vector machine, etc.), deep learning (convolutional neural networks (CNNs)), and fuzzy logic practices, which all belong to artificial intelligence (AI), have been used to improve fog forecasting. The CNN was first implemented in 1995 [101], and then case studies were performed by many researchers [102–106]. Fuzzy logic was first tested [107,108] and then improved [109–111]. The decision tree was also assessed by several researchers, including [87,88,112]. On one side, the use of AI leads to many advantages for fog forecasting including cost savings, increased accuracy, and faster predictions. On the other side, there are several barriers related to the use of AI for fog prediction such as those related to the accuracy of AI models, the complexity of the interpretation of AI models, and under-performing forecasts [45].

3.1. Radiation Fog

There are three main radiative processes that are related to the evolution of the radiation fog. First, the radiative cooling through the emission of longwave (LW) radiation at the top of the fog produces liquid water by condensation, preventing the depleting processes of liquid water. Second, fog droplets absorb the shortwave (SW) radiation in the near-infrared spectrum, causing heating, subsequent evaporation, and loss in the liquid water content (LWC). Third, fog evaporates from below, caused by a sensible heat transfer (HT) of the SW radiation from the ground to the fog. Generally, its life cycle is decomposed according to the behavior of the turbulent kinetic energy (TKE) [113,114]. The balance between turbulent mixing, radiative cooling, and droplet sedimentation is a factor that is greatly related to the life cycle of radiation [115]. Radiation fog involves three phases: the initiation phase, maturation phase, and dissipation phase.

3.1.1. Initiation Phase

The initiation phase, also known as the onset stage, is characterized by a strong inversion near the ground level and low intensity of turbulence. It corresponds to the radiative cooling of the ground when the surface radiates more heat than it receives, causing a temperature inversion in the lower layers. If the cooling of the ground propagates to higher levels, water droplets condense, producing a relative humidity of 100% and leading to the formation of fog. The stable inverse temperature promotes the formation and maintenance of fog. For instance, a strong, single-layer thermal inversion structure is conducive to fog development (pollutant enrichment), while a multi-layer weak thermal inversion structure tends to dissipate fog (inability of atmospheric pollutants to diffuse) [116]. The balance between radiative and turbulent processes is essential for the formation of the radiation fog [113,114]. Low turbulence is required for the vertical propagation of the radiative cooling [117,118]. The weak turbulence expands the fog and cooling layers promoting fog development and maturation. However, if the turbulence is too weak, saturation results in a significant dew deposit on the surface. On the contrary, strong turbulence enhances the mixing of fog and cooling layers contributing to fog dissipation or low cloud formation [119,120].

3.1.2. Maturation Phase

The maturation phase, also known as the development phase, is characterized by an increase in the TKE and by the appearance of a mixed fog layer. In the case that fog persists, it will continue to grow in depth and become more optically thick because of its higher content of liquid water. This will increase the radiative cooling in the fog layer at its top, while the lower part of the fog is shielded from cooling. The warmer soil from below heats the surface canopy at this point which in turn warms the lower part of the fog layer. At this time, its peak becomes the dominant radiative feature and cools to space [119]. The combined effect of these two processes is related to the reduction in the stability within the fog layer and the creation of a saturated adiabatic temperature profile [50,113,114,121].

3.1.3. Dissipation Phase

The dissipation phase is the result of the breakdown in the balance as one or more parameters suddenly change. The cooling from above or possibly the heating from below destabilizes fog layers and produces convective motions. Then, the unstable fog layers are intensified either by solar radiation (surface heating) or by an increase in wind intensity (turbulence fluctuation), mixing the saturated air of fog with the dry air above the inversion layer [115]. Upon the sun's elevation, its solar radiation influences the life cycle by warming either the fog layer or the ground. The solar radiation is partly reflected by the fog and partly transmitted to the ground. The latter will be heated by absorbing the radiation which gradually warms the lower fog layers and makes the atmosphere slightly unstable. In the case the turbulence is increased, the evaporation process speeds up from the bottom of the fog, reaching the stratus where the fog entirely dissipates. The intensity of heating

depends on the type of the surface, turbulence, and liquid water content. The higher the water content, the more fog absorbs the heat. This phase might be also affected by a change in radiative heating like the appearance of the stratus layer, heating from ground heat fluxes, and the drying of the air by fog droplet deposition on the earth's surface. The combination of these processes produces a young inhomogeneous fog that can appear and disappear randomly. In addition, the presence of a cloud layer above the fog may also lead to its dissipation by sending back the infrared radiation emitted by the top of the fog. The advection of the cloud layer above the existing fog will shelter fog and can be a probable mechanism for its dissipation [113,114,122].

3.2. Valley Fog

Pilié et al. studied the manner in which valley fog is formed. The following is concluded [123]:

- Nocturnal radiation from the surface and subsequent turbulent heat transfer from the air to the ground produce an early low-level temperature inversion and stimulate the downslope wind and upward return flow near the center of the valley. At this level, the deposition of dew at the cold surface creates the dew point inversion at the low level. The upward movement at the center of the valley carries the cool and dry air upward to cause the inversion to deepen.
- Almost 3 h before fog formation, the wind coming from the mountain provides a continuity for the downslope wind and prevents the upward movement of the air near the valley center. Cooling is restricted only to low and mid-levels of the valley which are the two levels in which fog will form. The downslope wind is mixed with warm air masses at mid-levels in the valley leading to the maximization of the cooling air in this zone. Then, a thin layer of fog appears.
- Later, the cold foggy air is mixed with almost saturated air, causing saturated air to propagate downward.

In the case valley fog is formed before sunrise, the surface warming is the result of a decrease in net radiation from the surface caused by fog forming aloft and heat conduction from subsurface levels. In the case valley fog is formed after sunrise, both surface warming and dew evaporation are caused by the sun. Then, the resulting instability at the low level stimulates vertical motions, causing the moist air from low levels to be mixed with cooler air. At this point, air saturation is reached, leading to fog formation.

4. Fog Frequency

The United States National Oceanic and Atmospheric Administration (US NOAA) runs the Global Daily database from over 8000 stations worldwide to make a useful comparison regarding the average annual fog frequency. A twenty-year period, between 1991 and 2010, is investigated to obtain precise meteorological data. The annual number of foggy days and annual cycle of fog widely vary according to local conditions and weather factors. The high occurrence of fog water usually occurs where water vapor is in excess such as in locations near the ocean, river, lake, sea, and other humid sites as well as where favorable conditions are present (i.e., cooling). Other factors including local conditions (altitude, type of land), mesoscale (distance to the coast, exposure to advection air masses), and synoptic scale (cyclonic scale) affect the duration and frequency of fog. The highest fog frequency has been observed in Washington/US (NDF = 311), Śnieżka/Poland (298), and Harz/Germany (284). High fog occurrence has also been detected in equatorial and subequatorial zones such as in Iquitos/Peru (102), due to the extremely high humidity and nocturnal radiative cooling. Fog occurrence is found to be high in montane tropical atmospheres such as in Quito/Ecuador (208). Further, in tropical and subtropical zones next to the coast, fog frequency is also high such as in Chile (189), where the region is influenced by cold oceanic air masses. In polar zones, the occurrence of foggy events is also high such as in Nuuk/Greenland (81) and Marambio/Antarctic (138), where advection fog is dominant. However, fog frequency all over the world has shown a significant decrease.

Statistical results show that the strongest relation to fog occurrence is air pollution. In the case air pollution becomes less severe, environmental factors such as wind speed, urban heat island (UHI), relative humidity, and inversion layer become decisive in controlling its occurrence and duration [124]. Literature studies reported a decrease in the majority of fog stations worldwide. Williams et al. reported that the change in regional climatic conditions such as the ongoing intensification effect of UHI or atmospheric circulation leads to an increase in air temperatures contributing to a decrease in the fog frequency in southern California [89,125]. Aerosols are found to have a direct relation with fog evolution [126]. For instance, Vautard et al. investigated weather information from over 300 stations in Europe and reported that fog frequency has decreased in the last 30 years. The main reason was attributed to a strong decrease in the emissions of sulfur dioxide since the late 1980s. Air quality has improved, and therefore, the number of condensation nuclei, which act as the substrate on which water vapor condenses, is reduced, leading to a decrease in fog occurrence [127]. Fog frequency has been also studied by Araujo et al. and Goncalves et al. in the metropolitan region of Sao Paulo between 1993 and 2005 [128–131]. They found that the decrease was mainly correlated to the decrease in the relative humidity and increase in air temperature caused by the UHI intensification. Han et al. observed an increase in fog frequency in the North China Plain between 1980 and 2010 [132]. The main reason behind this increase is attributed to the decrease in air quality. Fu et al. found that fog frequency in the North China Plain increased before 1995, fluctuating between 1995 and 2003, and has decreased since then [133]. The decrease is attributed to the improvement in air quality. The same scenario was also observed by Quan et al.: an increase in fog occurrence between the 1970s and 1980s and a decrease after 1999 [134]. Ding and Liu stated that the decrease in the relative humidity causes this trend in China [135]. In Japan, fog occurrence has also decreased, as reported by Belorid et al. [136]. This was attributed to the decrease in the nocturnal radiative cooling rates. Most of the fog frequency in Iran decreased between 1985 and 2005 over 100 stations except for three stations. Rahimi stated that the increase in temperatures was found to be the main cause for this decrease [137]. The same results were found in Thailand between 1951 and 1995 at over 50 stations [138]. Giulianelli et al. also stated that fog frequency has decreased over the last three decades which is in agreement with other results [139]. They suggested either a decline in the available condensation nuclei or an increase in temperatures.

5. Fog Nucleation and Activation

5.1. Fog Nucleation

The formation of fog water requires relatively high humidity conditions ranging from undersaturated to slightly supersaturated conditions [140]. The presence of atmospheric aerosols is a key factor for droplet formation, where they can grow in size more easily in a saturated atmosphere [44]. The process of forming the droplet nuclei, known as the nucleation scavenging process, is of great significance for cloud, particle, and fog formation [141]. The presence of hydrophilic inorganic species including sulfate, nitrate, and ammonium (SNA) and soluble elements including magnesium and calcium plays a vital role in fog formation by acting as CCN. The presence of water-soluble organic carbon (WSOC) has been pointed out to modify the hygroscopicity of aerosol particles and enhance their tendency to act as CCN [142]. The availability of trace metals like copper, manganese, and iron also plays a significant role in aerosol–fog interactions by acting as catalysts for aqueous-phase reactions.

Fog formation and droplet growth highly depend on the physico-chemical character of CCN. Thus, they are expected to be formed in environments with large CCN concentrations associated with low levels of supersaturation [16,143,144]:

- Heterogeneous nucleation (nucleation scavenging): It is the condensation of water vapor into a subset of particles in the presence of foreign condensation nuclei. Many atmospheric aerosols (AAs) are hydroscopic in nature. The presence of hydrophilic particles in the atmosphere is an important factor that facilitates the condensation

of water vapor into droplets. The resulting droplet diameter ranges from several micrometers to tens of micrometers. The nucleation of supersaturated water vapor on aerosol wettable particles, whether soluble or insoluble, will be responsible for fog droplet formation. Particles having the tendency to nucleate liquid fog droplets are known as CCN [145,146]. Among the factors that determine the ability of particles to act as CCN at a given level of supersaturation, are the size, shape, and wettability of particles, solute content, surface tension, solubility, supersaturation level, and the presence of surface-active substances. In the absence of suitable particles, fog will not be able to form because very high supersaturation levels are required for the condensation of water vapor, and such levels usually remain below 10% and even below 1% [40,143].

Numerous types of AA particles are capable of acting as CCN. Some of the AAs are generated from natural sources (sea spray, volcanic debris, biogenic aerosol, etc.), while others are derived from human-made activities (industrial emissions, agricultural activities, biomass burning, fossil fuel combustion, etc.) [23,147]. In the presence of small amounts of water supersaturation, AAs tend to grow spontaneously to form fog droplets. Particles containing water-soluble compounds are more desirable to act as CCN over those containing largely insoluble compounds [148]. Particles with diameters ranging from 0.001 to 0.2 μm play a significant role in fog/cloud and precipitation microphysics. In fogs, aerosols are activated and grow into droplets whenever their size is greater than 0.1 μm and smaller than 1 μm. This means that the accumulation-mode particles are mainly responsible for fog formation. Particles with diameters greater than 1 μm may grow but without being activated [148–150]. In the case the particle concentration is high and/or the supersaturation level is low, the minimum size of the particle required for activation is 0.5 μm [150]. The accumulation-mode particles are formed through the coagulation of smaller particles that belong to the Aitken nuclei (<0.1 μm) or from the condensation of vapors into existing particles, forcing them to grow [151]. They are characterized by their long residence time and high concentrations compared to other modes. The accumulation-mode particles account for a substantial fraction of the total aerosol mass and have the greatest surface area. This makes them of high importance to atmospheric heterogeneous chemistry. Such particles are released through the incomplete combustion of coal, oil, wood, gasoline, etc. They consist of SO_4^{2-}, NH_4^+, NO_3^-, metal compounds (Cu, Ni, Cd, Fe, Zn, Mn, Pb, etc.), organic compounds, and elemental carbon (EC) [152].

More recently, organic aerosols have received particular attention. Organic CCN occur naturally or though anthropogenic activities and could be produced from primary and secondary organic aerosol (SOA) sources. The main primary sources of organic CCN include biogenic emissions, biomass burning, vehicle exhaust, etc. The oxidation products of soot, secondary anthropogenic aerosols, and secondary biogenic aerosols are among the main secondary CCN sources. Primary biogenic aerosols are those containing fragments, reproductive materials, whole organisms, and decaying biogenic organic aerosols. The main secondary biogenic aerosols include the oxidation of VOCs released from biological organisms [153]. Some of the organic aerosols that have proved their efficiencies in acting as CCN are as follows:

1. Total organic carbon (TOC)/dissolved organic carbon (DOC): A substantial amount of organic carbon (OC) is found in fog water. Its concentration ranges from 1 ppm in remote marine environments to 100 ppm in polluted radiation fogs. Very high concentrations have been measured in biomass-burning-impacted atmospheres which vary between 100 and 200 ppm (mgC L^{-1}). Such high levels were obtained at Mt. Tai in China at a high altitude (1500 m), released from abundant smoke from agricultural combustion [22]. Most of the organic fraction in fog is considered to be DOC which reflects the abundance of volatile organic carbon (VOCs) in the atmosphere. It has been found that DOC constitutes about 80% of the TOC in the aqueous phase. Thus, DOC is a nearly quantitative measure of TOC in the condensed phase of fogs [154–156].

2. Monocarboxylic (MCA) and dicarboxylic acid (DCA): The predominant species belonging to MCA in fogs are formic (HCOOH) and acetic (CH_2COOH) acids, while DCA species such as oxalic acid, malonic acid, and succinic acid constitute only a small fraction of the total water-soluble organic species in the atmosphere [153]. Previous work demonstrated that mono-, di-, and poly-functional carboxylic acids are the major contributors to the water-soluble organic matter in fog water [142,154,155].
3. Humic-like substances (HULIS): They are fine particles having good water solubility consisting of aliphatic and polysaccharide substructures. They originate from biogenic sources and comprise a large fraction of OC. They are found in fog droplets with a similar scavenging ratio to that of inorganic ions. These substances affect the physicochemical properties of aerosol particles as well as the formation of CCN. HULIS have been characterized as surface-active materials produced from the oxidation of gaseous precursors on aerosols in the atmosphere. Their presence increases the surface-active nature of fog water and decreases surface tension contributing to a higher uptake of hygroscopic organic vapor-phase compounds [153,157].
4. Bacteria (0.25 to 8 μm in diameter): A group of very metabolically diverse, prokaryotic, and unicellular microorganisms. They are found to be temperate vegetation zones, such as raw crop areas (high primary production) and desert areas (relatively low production). Living and dead bacteria have been observed in cloud water, fog water, and rainwater as well as in different parts of the atmosphere (boundary layer, upper troposphere, and stratosphere (up to 41 km above sea level)). Among the bacteria able to act as CCN at low saturation ratios (from 0.07% to 1%), are the plant pathogenic bacteria Erwinia carotovora, as well as Gram-positive and Gram-negative bacteria (Micrococcus agilis, Mycoplana bullata, and Brevundimonas diminuta) [153].

Therefore, AAs are responsible for the acceleration and intensification of fogs, especially in urban areas because of the presence of more hygroscopic particles in the atmosphere that may regulate its optical thickness [44]. The polluted atmosphere is capable of having eight times more droplets with half the size and twice the optical depth and surface area, causing higher obscurity than unpolluted atmospheres [158].

5.2. Fog Activation

For a complete understanding of the activation process, the size distribution and chemical composition of AAs must be taken into consideration. The size of AAs is highly connected with water vapor supersaturation in fogs which is a key for the activation process. Particles are divided into two categories: activated and non-activated particles. In the case the critical supersaturation level (SScr) is lower than the actual supersaturation, particles are activated. In the case the SScr is higher than the actual supersaturation, particles grow to their equilibrium diameters by capturing water but remain inactivated [144,159]. Thus, the ability of CCN to be activated into droplets is determined by the physical and chemical properties of AAs [150,160]. The spontaneous growth of CCN into fog droplets under supersaturated water vapor conditions is described by the classic theory of Kohler. The rate of droplet growth depends on the initial size of aerosols and their solubility [161]. CCN activation depends on the interrelation between the Raoult effect—known as the water activity—and the Kelvin effect. In the Raoult effect, the potential of CCN activation increases with decreasing water activity or increasing solute concentration. In the Kelvin effect, the potential of CCN activation decreases with the decreasing size of the water droplet or increasing surface tension. Through the Raoult effect, certain aerosol particles absorb water vapor at a relative humidity below 100%, and then they grow in size. In this way, they reach sufficient diameters for the Kelvin effect to occur leading to the creation of droplets, absorbing water vapor at their disposal. The transition from the Raoult effect to the Kelvin effect is the activation process of CCN [159,162]. Therefore, aerosols are considered to be "activated" once these droplets reach a certain size, where they are more easily grown within a saturated environment [161]. AAs might be hydrophobic particles (will not be activated at all) and water-soluble particles possessing hydrophilic sites that

allow activation at higher supersaturation or have some water-soluble components that will be activated at lower supersaturation.

5.3. Effects of CCN

The radiative effects of aerosols on fog may be classified as direct, indirect, and semi-direct [163]. First, aerosols may scatter and absorb solar radiation (short and long waves). Second, aerosol particles may scatter, absorb, and emit thermal radiation. Third, aerosol particles may act as CCN. The first two mechanisms are the direct effects, while the last one is the indirect effect. The semi-direct effect is a consequence of the direct effect of absorbing aerosols [164–167]. Direct radiative forcing of aerosols may either cool (nitrates, sulfates, etc.) or warm the atmosphere (black carbon (BC)), depending on the proportion of the scattered light to the absorbed light. The scattering aerosols have a cooling effect on the atmosphere, whereas the absorbing aerosols have a heating effect on the atmosphere. Absorbing CCN is also known to influence fog formation because when air temperature increases, the relative humidity is reduced, prohibiting the appearance of fog or shortening its life in the case it is formed through enhancing droplet evaporation [168]. This is one of the main reasons for declining fog frequency along with the effects of urban heat intensification [125,169–171]. Both direct and semi-direct effects of aerosols have been studied by Bott using numerical simulations. The latter shows that urban aerosols containing particularly soot absorb solar radiation and thus increase the cooling rate of the surface and accelerate fog formation. This is the direct effect. The same aerosol that absorbs more solar radiation leads to fog dissipation. This is the semi-direct effect [163]. The first indirect effect (Twomey or cloud Albedo) of aerosols on fog water was studied experimentally by Hudson on the west coast of the US subjected to air masses of different origins [172]. He showed that sea (maritime) fog comprises few water droplets with large diameters, while urban (continental) fog contains more droplets but that are smaller in size due to two reasons. The first reason is that aerosol concentrations in oceanic regions are lower than those in continental or polluted areas. An increase in aerosol concentrations leads to an increase in fog droplet concentrations. However, Bott and Trautmann show by means of numerical simulations that the higher the concentration of aerosols, the lower the supersaturation in fog leading to completely opposite effects of those observed by Hudson [69]. Indeed, the lowest concentrations of droplets formed in the case of low total aerosol concentration have larger diameters, and they are unable to absorb the excess water vapor. The second reason is related to the physico-chemical properties of aerosols. Sea-salt aerosols are more hydrophilic than those of urban sources. They tend to absorb water more quickly, leading to lowering the ambient supersaturation in water vapor. They slow down the activation rate of new aerosol particles in water droplets. The second indirect effect (cloud lifetime or Albrecht) concerns the impact of cloud microphysics on the lifetime of fog. The number concentration of CCN largely determines the "cloud droplet number concentration" known as CDNC and affects indirectly the LWC through droplet sedimentation. With a low CCN number, the condensation of water is limited by the available surface area, resulting in higher supersaturation. Fog droplets have large droplet size distribution for a given liquid water path, enhancing the rate of droplet sedimentation and decreasing the cooling rate and thus the production rate of liquid water content, leading to a shorter life of the fog. In contrast, with a large number of CCN, the condensation will be sufficient, resulting in a lower supersaturation. The droplet size will be smaller with a narrower droplet size distribution for a given liquid water path, slowing down the rate of droplet sedimentation and increasing the cooling rate and thus the production of liquid water content, making fog more intense and denser which will delay its evaporation process. Therefore, the concentration of CCN has a strong impact on the life cycle of fog [173].

5.4. Droplet Size Dependence

The chemical composition of fog varies according to the droplet size mainly due to two reasons. The first reason is the inhomogeneous chemical composition of the CCN, while the second reason is the differences in the solubility rates of the gas uptake by small and large fog droplets. Smaller fog droplets are much more concentrated and grow faster than larger droplets as long as there is enough water vapor for condensation. The possible explanations for the enrichment of major inorganic solutes and organic carbon in smaller fog droplets include the higher dissolution rate of CCN in smaller amounts of water, differences in condensational growth, and the higher surface/volume ratio of the small droplets promoting greater surface area for gas/liquid transport and consequently more chemical reactions. The distribution of the chemical components across the aerosol size distribution depends on the chemical composition of the CCN on which the fog droplets form. The smallest activated droplets are formed on the smallest CCN, whereas the largest droplets are formed on the largest CCN. Thus, species contained in small accumulation-mode particles (e.g., SNA) are enriched in smaller fog droplets, and species originally found in the coarse mode such as calcium, magnesium, chloride, and sodium are enriched in larger fog droplets. However, large droplets are unnecessary to be more diluted than the smaller droplets. Through numerical simulations, Pandis et al. stated that droplets whose diameter is 20 μm have a bigger solute concentration than 10 μm droplets by a factor of 3.6 [174]. Thus, fog chemistry varies from one case to another with droplet size including the rate of condensation on CCN, rate of dilution, rate of soluble gas uptake, and rate of chemical reactions (e.g., S(IV) oxidation) [16]. For a given LWC, the levels of concentrations are affected by the variability in the concentrations of the dissolved pollutant per unit volume. If the LWC decreases (a decrease in the number of fog droplets per unit volume of air), the concentrations of fog water increase for a given concentration of pollutant per unit volume of air. For a given droplet size, the liquid-phase concentrations are governed by the ratio of the concentration of the dissolved pollutant per unit volume of air to the number of droplets per unit volume of air [4,175].

6. Fog Impacts

Globally, fog negatively affects a wide variety of human activities. These effects range from inconvenience to annoyance and from high costs to deadly consequences. However, there are also some positive benefits as well, especially those related to water supply applications, agricultural activities, and ecosystems [5,11,176,177].

6.1. Air Quality

The high fog frequency in a particular region affects the air quality of that region. The most popular effect of the fog–aerosol interaction is commonly known as haze or smog (a combination of smoke and fog) [178,179]. There are mainly two forms of smog: the classical smog (London type) [180] and the photo-chemical smog (Los Angeles type) [181]. The latter is caused by the interaction of CO, O_3, VOCs, and NO_x with solar radiation and occurs near mid-day, especially during the summer season [182]. The classical smog is caused by the interaction of SO_2 with PM and takes place in winter and autumn near the ground at temperatures around 0 °C in windless conditions. Once the haze fog contains the atmospheric pollutants, air quality decreases. The trapped NO_x and HCs near the ground surface are converted into harmful O_3. The greenhouse gases (GHGs) highly spread in the air are also trapped within the stable layer of the inversion zone. All these trapped pollutants in the inversion layer remain suspended and will have an adverse impact on the ecosystem and climate change. Recently, a new form of smog has been recognized in Poland known as the Polish or Dusty smog, because high volumes of dust ($PM_{2.5}$ and PM_{10}) have been detected [183]. In addition, fog processing results in an increase in the secondary organic aerosols, their size, and their loadings due to the high occurrence of aqueous-phase reactions [184]. An increase in total particulate matter (PM_1) is reported in Hisar and Kanpur. Coagulation processes during foggy days also lead to an increase

in particle size [185]. Gas-to-particle conversion processes increase due to the presence of chemical reactions in the medium which acts as a physico-chemical process, resulting in high concentrations of SNA.

6.2. Human Health

Depending on the chemical and physical nature and composition of fog droplets, fog water has direct and indirect adverse effects on human health (skin and eye damage, respiratory and radiation diseases, secondary health effects, etc.) [186–188]. Exposure to fine aerosol particles, especially acidic species, nitric acid sulfur dioxide, sulfur oxide, and microbes, increases the morbidity and mortality of diseases in the respiratory system, cardiopulmonary system, throat irritation, cardiovascular system, muscular system, and lung cancer [186,189]. Exposure to sulfuric dioxide tends to affect the respiratory tract, leading to aggravation in asthmatics. Exposure to nitrogen dioxide demonstrates a slight unfavorable impact on the respiratory system at ambient concentrations. The inhalation of fog with high sulfuric acid concentrations has no clear influence on pulmonary activity, only a slight impact on the respiratory system [190,191]. The relation between asthma patients and air pollution or meteorological factors has been further investigated over a period of two years on 102 adults (44 patients are non-atopic while the rest are atopic). The results show that hospital visits increase on foggy days compared to fog-free days, especially on days with lower pH and low levels of gaseous air pollutants. An increase in hospital visits is observed when the concentrations of NO_2 and NO are low in the case of non-atopic patients. Meanwhile, hospital visits of atopic patients increase with decreasing NO_2 and SO_2 concentrations. The reason might be possibly due to the scavenging of these pollutants by fog which could increase the acidity of fog water. Tanaka et al. state that adverse bronchial epithelium problems might be caused by several possible mechanisms associated with H^+, O_3, H_2SO_4, and HNO_3 [186]. Thus, the fact that airway resistance caused by acidic pollutants increases might be due to the reduced absorption capacity of the hydrogen ions in the airway mucus [192]. The neutralization of naturally occurring acid fog with ammonia may reduce the impact of the inhaled acid aerosol during foggy days. Ammonia might neutralize about one-quarter of inhalable acid in healthy volunteers [193]. Concerning the meteorological conditions, the high ozone concentrations and the low day-to-day temperature differences lead to an increase in hospital visits for non-atopic patients. In both cases, high water vapor pressure favors the increase in hospital visits [194]. Researchers have recently found that fog inhalation is responsible for changes in breathing problems and cough for healthy subjects. For this aim, a study has been carried out on the respiratory response induced by fog, implementing a probable way to decrease respiratory problems. The effects of no drug, nedocromil sodium (NCS), and placebo were evaluated on 14 healthy subjects during fog inhalation [191]. The results show that NCS is able to reduce changes in the breathing pattern and inhibit fog-induced cough. N-nitrosodimethylamine (NDMA) in fogs proves its efficacy in acting as a source of potential carcinogens. Notable concentration levels of NDMA are found in the range of 7.5–397 ng L^{-1} in fog [188]. Further, exposure to smog fog can have a short-term and long-term negative impact on the cardiovascular and respiratory systems, causing severe illness [195]. Most recently, the presence of metals (Cu, Zn, Sr, As, Pb Na, Mg, V, Ni, Ba, Cr, etc.) detected during a fog-haze event showed that their risks evaluated on children and adults exceed the precautionary level of 10^{-6} by factors of 1.32 and 5.29, respectively [116]. In addition, the presence of O_3, PMs, and NO_2 in smog events increases the development of cardiovascular illnesses, respiratory problems, and ischemic heart disease (IHD), especially for those who suffer from various health problems [196,197].

6.3. Transportation and Economy

Fog affects a wide range of human activities. It may cause high costs, inconvenience, and even death [198]. It reduces visibility which acts as a barrier for driving, sailing, or even flying [199]. The total financial and human loss for fog-related transport accidents (sea, air,

and land) is approximately the same as that of tornadoes, hurricanes, and winter storms in some cases [11,56]. Adverse visibility and ceiling conditions lead to 35% of weather-related accidents in civil aviation and cause, on average, 168 mortal casualties per year. In fog-prone regions, fog is cited up to 10% of the time as the principal source of accidents, especially in multiple-vehicle crashes. In the case of dense foggy events, airports refuse to accept planes and cancel take-offs due to security reasons such as the cases reported in Canada and the US [6,200]. This may cost the airlines between USD 5,000 and USD 25,000 for any delayed or canceled flight. Concerning sea transportation, many shipping operations are either stopped or slowed-down in the case where the visibility is lower than 0.5 km, and the economic losses typically range between USD 10,000 and USD 25,000/day/ship and cost millions of dollars for moderately active ports [11]. The estimation of the economic losses in 2006 associated with dense fog events in the pre-Christmas period was at least GBP 25 million at seven British airports. Approximately 50 people die yearly in Canada due to vehicle accidents in which fog is the main cause. Fog-related accidents resulted in 13,720 deaths between 1995 and 2004 in the US. The presence of fog led to 1122 fatal air accidents and killed around 229 people in the US between 1982 and 2013. In addition, the Aviation Safety Network reported that six planes have crashed in Iran due to poor visibility conditions, and 353 persons have been killed since 1988 [201]. Overall, a huge number of deaths is reported worldwide in fog-related ship collisions, vehicle crashes, and aviation [199]. An annual increase in road accidents, deaths, and injuries was reported in India between 2017 and 2019 due to reduced visibility during foggy events [202]. Fog also has a direct impact on military rescue operations. It contributes to property damage, supply delays, and event cancellation. It affects the travel time reliability and the operations of schools and colleges [11,199].

Numerous studies were previously conducted to develop methods for artificially removing fog from airports in the early 1970s. The main purpose was to see how fog can be prevented from a specific area as in the airport or shipping port. Since fog is formed in a narrow droplet size range, its dissipation might occur by increasing its droplet size through coalescence processes. It is suggested that using specific amounts of hygroscopic particles (e.g., coarse particles) such as sodium chloride (NaCl) ameliorates the visibility and might be one of the possible ways for fog dissipation [203,204]. Plank et al. reported another way for fog dissipation that is based on the turbulent mixing of dry air above the inversion layer with the saturated air in the fog by a helicopter's downwash [205]. Other recent studies implemented the use of the acoustic field at airports for fog precipitation. This technology helps to disperse the different phases of a fluid under specific conditions. In the case the air is efficiently saturated, the droplet size increases (droplet coagulation) under the influence of the acoustic field leading to fog precipitation [206].

6.4. Benefits

Despite the severe negative impacts of fog around the world, it proves its beneficial impacts in terms of water applications, agricultural applications, and ecosystems. Fresh water scarcity has become a major problem facing humanity and is expected to further intensify due to the rapid increase in population density and climate change. Fog harvesting started between 1901 and 1904 in South Africa, and continuous progress has been achieved regarding this issue. The number of its research interests addressing technical aspects, policies, community development, economics, and impacts has increased, in addition to the increase in the operational fog water collection systems over time [207–211]. The number of publications on fog water collection revealed a growing interest and has increased from 4 (between 1981 and 1990) to 223 (between 2011 and 2020), most of them focusing on the experimental or technical part of fog collection [210]. An efficient option to overcome this issue is fog water harvesting using either the standard fog collector (SFC) or the large fog collector (LFC) using mesh nets (Rachel nets). The mesh materials can be nylon, polyethylene, and polypropylene (Shade cloth) which are able to capture different quantities of water from fog [212]. The size of the SFC, which was developed by Schemenauer and

Cereceda, is 1 m^2, while that of the LFC varies between 40 and 48 m^2, and the ratio of width to height must be between 2.5 and 3 [213]. The number of fog collectors depends on many factors such as fog thickness, duration, and frequency, along with the water demand and financial capacity. The collectors are placed perpendicular to the prevailing wind [214]. The cost of the LFC is regulated by the price of mesh varying between USD 25 and 50 per 1 m^2. Fog collection starts when fog droplets come into contact with the mesh net standing perpendicular to the fog-carrying winds where they are impacted. As fog droplets increase in size by coagulation, they find their way to the collection reservoir by gravity. In the fog harvesting project in Morocco, the price of the mesh net is USD 5/m^2 due to the low-cost material. Successful fog harvesting projects performed in Namibia [215], South Africa [216], Morocco [217], Chile [218], Saudi Arabia [219,220], Egypt [221,222], Azerbaijan [223], Ecuador [224], Oman [225], Spain [226], etc., have proved its possibility to be a potential alternative for conventional water resources, particularly in dry regions characterized by high fog frequency. In some cases, water collected may even adhere to potable quality standards, unless the fog collection is performed near polluted environments (urban and industrialized areas) [227]. Fog collected at Cape is found to be of high quality and fit for human consumption. Choosing the best and optimal sampling site relies on many features as well including the terrain characteristics, accessibility, potential to harvest the biggest fog volume, and the proximity to a water-poor community [208,214]. Fessehaye et al. suggested that one of the suitable locations can be a high mountain range close to a coastline [208]. The yield of the collector water is in turn dependent on the persistence of high-density foggy events and the moisture content. The most important aspects that should be taken into account regarding the water quality are the chemical composition of fog water and the probable alteration in fog composition during storage [214,216]. So far, no negative impacts on vegetation, animals, humans, and ecosystems have been reported in fog harvesting projects [214]. Additionally, the deposition of fog water is found to be critical to agricultural operations in Mexico, Chile, and other countries around the world. Fog water is found to be important for the growth of the giant Redwood trees in the US (California). It plays an important role in the physical interactions within plant canopies and their growth and physiological conditions [5]. Fog proved its importance for the development and growth of tress and plant species in coastal and alpine zones, flora and fauna in desert areas, and biota in coastal and alpine areas [89,178,228–231]. In addition, fog water is an important atmospheric deposition phenomenon for washing and cleaning the atmosphere due to the continuous scavenging and depositing effects of air pollutants.

7. Fog Collectors

Fog water collection has a long history. So far, several techniques and collectors have been developed and applied for the collection of fog samples including active and passive fog collectors. Passive collectors solve the problem of unavailable main power at the site. However, they might be contaminated by an unknown fraction of drizzle, conventional precipitation, and horizontal wind-driven rain. Many experiments employ passive fog collectors in which wind is the principal factor that drives fog droplets to the sampler where they are collected via their impaction on strings. The deposition plate is the simplest passive fog sampler. It includes a horizontal plate on which fog droplets are settled. The next fog collector is the string screen sampler. Fog droplets are collected through their impaction on a string screen. The droplets adhere to the string, move down along the string, and are collected in trays [232]. In active fog systems, the air flow containing water droplets is forced by mechanical means using either forced flow through rotating motors or fans and pumps to achieve the same end. The first type of active collector is described by Jacob et al. [233]. In this type, fog condenses on the wires, the baffle smoothes the flow of the air, and the fan pulls the air past the wires. Fog droplets collected on the wires move down the wire and are then collected in a clean bottle. The Caltech Active Strand Cloud Collector (CASCC) is another type of active fog collector developed

by Daube et al. [234] and then modified to include droplet-size fractionation [235]. The CASCC has been used in numerous field studies [16,18,236–244]. Fog water droplets are collected by inertial impaction on Teflon strands. The strands are inclined 35 degrees from the vertical. The collected droplets condense together and flow down into a Teflon trough by aerodynamic and gravity forces. Samples are then delivered to the collection bottle. Larger CASCCs are described in Fuzzi et al. [245], Minami and Ishizaka [246], and Sasakawa and Uematsu [247]. A similar but smaller collector (CASCC2) was developed by Demoz et al. [248]. However, problems might happen in the case where the ambient temperature is below the freezing point of liquid water. In this case, the collected fog droplets will be frozen immediately. To overcome this problem, collectors with heating options are developed and applied in several experiments [249]. For this purpose, the CalTech heated rod cloud water collector (CHRCC) is developed. The collection surface of the CHRCC is made up of stainless steel rods that have the ability to be heated internally in the case the temperature decreases below 4.5 °C. In this way, the collected fog water droplets melt again and find their way to the collection bottle [250]. Heating should be applied only when the ventilator is turned off to minimize the evaporation that alters the collection efficiency. The characteristics and operating conditions of all these collectors are described in Demoz et al. [248]. Further development involves the multi-stage fog collectors that resolve more than one-size fraction (sf-CASCC) [236,251,252]. A five-stage cascade rectangular jet impactor is also used by Straub and Collett [253] and Moore et al. [254] for fog and cloud collection. The main drawbacks of an active fog collector are its high consumption of electricity, and its deployment is restricted to sites that provide main power. Therefore, it is necessary to develop a new active collector to overcome electricity problems. For this issue, a new type of CASCC collector has been developed, known as MiniCASCC. It is the smallest active fog collector that allows further decreasing the cost of building and operating the device [255].

8. Fog Water Chemistry

Fog consists of water droplets suspended in the air whose diameters typically range from 1 to 100 μm. The LWC is generally smaller than that of rain and cloud waters and varies between 0.01 and 0.5 g m^{-3}. Chemical species found in fogs exist in three phases as gases, interstitial aerosols, and inside the droplet as liquids. The physico-chemical relations among particles, gases, and fog droplets affect fog chemical composition. The incorporation of gases and fine particles into the aqueous phase is a multi-step process. The molecules are first diffused toward the liquid surface where mass transfer across the gas/liquid interface and chemical reactions occur (if any). After that, the species are diffused into the fog droplet [244,256]. The overall atmospheric concentration of any species "i" in fogs is given by Equation (1) [257].

$$[C_i]_t = [C_i]_l * LWC + P_i(R * T)^{-1} + [Ci]_a \quad (1)$$

where $[C_i]_t$ is the total concentration of any species i (mol m^{-3}), $[C_i]_l$ is the concentration of the species "i" in the droplet phase (mol m^{-3}), LWC is the liquid water content (dm^3 m^{-3}), P_i is the partial pressure of species "i" in the gas phase (atm), R is the universal gas constant (m^3·atm K^{-1} mol^{-1}), T is the temperature (K), and $[Ci]_a$ is the concentration of the species "i" in the aerosol (mol m^{-3}).

The LWC is an important microphysical parameter that controls fog chemistry. The solute concentration in fog water is proportional to its atmospheric loading but inversely proportional to the LWC which decreases with increasing the LWC. However, instead of falling along a straight line, it has seen an exponential function of the trend. An increase in LWC in fog water leads to a diluting effect of the solute [156,258–262]. However, LWC alone cannot always explain the temporal evolution in terms of the concentrations [244,246]. The latter is determined by many factors in addition to LWC such as the rate of the chemical reactions, gas scavenging, air masses, and other microphysical properties. Other studies show that no relation exists between LWC and DOC given the differences in gas and

particle-phase organic carbon concentrations [22,244]. During the formation stage, the concentration of pollutants tends to be the highest under the high-temperature inversion where the LWC and the surface area per unit volume (S/V) are the lowest. However, the ratio of surface to LWC is large, meaning higher scavenging efficiency with respect to the dilution effect. Therefore, the concentrations stay at high levels. During the maturation stage, the pollutant concentrations tend to decrease dramatically over the course of the fog event. In this phase, the surface area will be higher leading to an increase in the scavenging potential of pollutants and their subsequent deposition. Further, the LWC also rises with the increase in the supersaturation levels in the maturation period of fog leading to a dilution effect. During the dissipation phase, the surface area will be lower again, meaning that the scavenging potential is lower, and thus, the deposition will be smaller. In addition, the LWC is lower, and the ratio of surface to LWC increases, contributing to a gradual increase in the pollutant concentrations [227,263].

8.1. Processes Controlling Fog Chemistry

Fog influences the ecosystem by concentrating, transforming, and depositing atmospheric pollutants into the surface. The interactions between aerosols and fog alter the chemical composition of fog droplets which is governed by aqueous-phase reaction rate and the scavenging effect. Fog droplets can effectively trap pollutants near the surface and enhance the formation of secondary aerosols through liquid-phase oxidation reactions leading to an increase in the aerosol concentration [178,254,264]. Fog may also decrease the ambient aerosol concentration by removing part of the aerosol particles through the continuous scavenging and settling effects [116,265,266]. A decrease in the atmospheric particle loading could increase the ambient supersaturation when ignoring the changes in the source term of supersaturation. In this way, the CCN activation rate increases, altering the chemical and microphysical characteristics of fog [168].

8.1.1. Oxidative Reactions

Fog droplets are considered efficient scavengers of boundary pollutant layers and may provide a favorable environment to produce strong acids through aqueous-phase reactions [22,154,266]. It is evident that aqueous-phase chemistry in fog droplets could lead to a substantial formation of SOA material by transforming volatile gas-phase species to less volatile (semi-volatile) material that remains in the particle phase upon drop evaporation [267]. The size of the new products is larger than their original size [184]. The aqueous-phase oxidation is of special interest for SO_2 and NO_2 during the occurrence of fogs. The production of S(VI) from the oxidation of S(IV) is one of the most important liquid-phase reactions altering fog acidity, reducing visibility, and causing negative effects on human life and climate [233,266,268]. The production of sulfate may occur in both phases; however, it will be faster in the aqueous phase. One possible mechanism for the oxidation of SO_2 includes the gas-phase oxidation of $SO_{2(g)}$ to sulfuric acid ($H_2SO_{4(g)}$), followed by condensation of $H_2SO_{4(g)}$. Another possible mechanism might be the dissolution of $SO_{2(g)}$ into an aqueous solution to form sulfurous acid ($H_2SO_{3(aq)}$), followed by the aqueous conversion of the latter to $H_2SO_{4(aq)}$. The production of nitrate (NO_3^-) is also possible during fog events through an aqueous-phase reaction. Even though the direct oxidation of nitrogen dioxide (NO_2) and nitric oxide (NO) is theoretically possible, their kinetics are very slow to produce significant amounts of NO_3^-. The high NO_3^- amount produced through the aqueous-phase reaction is mainly derived from the dissolution of nitric acid (HNO_3) or dinitrogen pentoxide (N_2O_5) and nitrate aerosols. Another pathway might be the oxidation of NO_2^- to NO_3^- in the liquid phase after the production of NO_2^- from nitrous acid (HNO_2) [257,269]. Many oxidative reactions are kinetically affected by catalysts and are photo-chemically induced in oxidative environments and in the presence of trace metals that can act as redox catalysts. The major oxidants are H_2O_2, O_3, hydroxyl radical (OH.), O_2 (auto-oxidation), and sunlight. The traces are organic materials such as HCs, soot surfaces, and dust or metals such as Fe, Mn, and Cu.

8.1.2. Acid–Base Interaction

The high acidity of fog water causes severe damage to the environment because of its high potential to destroy materials, vegetation, and human health. Fog is considered acidic when its pH is lower than 5 and alkaline when its pH is higher than 6. The main strong acidic compounds emitted to the atmosphere are H_2SO_4 and HNO_3. The acidity of fog water differs from one region to another due to the presence of many acidic species. In remote environments, fog water droplets are partly acidified due to the dissolution of carbon dioxide (CO_2). In regions where the pollution is critical, further acidification occurs by scavenging H_2SO_4 and HNO_3. In polluted and pristine atmospheres, low molecular weight (LMW) carboxylic acids, such as formic and acetic acids, are the major contributors to increased fog water acidity. Carbonyls and dicarbonyls also have a significant role in increasing acidity due to their high levels in the air and their capability to react with the dissolved SO_2. However, the presence of some alkaline species (especially NH_4^+, Ca^{2+}, and Mg^{2+}) titrate and neutralize the free acidity under high nitrate and sulfate conditions. They react with HNO_3 and H_2SO_4 at high humidity to produce concentrated ammonium and sulfate salt droplets. A substantial fraction of sulfur dioxide also reacts with dust particles to form sulfate. Thus, dust aerosols have an important role in neutralizing fog acidity. So, in a way, the presence of fog leads to efficiently neutralizing its acidity [268].

8.1.3. Fog Scavenging

Fog scavenging is the process through which the suspended particles in the atmosphere are transferred into the aqueous phase of fog water [270]. Organic matter in fog droplets comprises a wide variety of compounds that might enter fog drops either through particle scavenging or through absorption from the gas phase, depending on whether the organic compound is found primarily in the gas or particle phase in the atmosphere; therefore, its entry route into fog drops will differ. Fog scavenging processes reduce the atmospheric loading of aerosols by promoting wet removal and modifying the particle size distribution of aerosols and their hygroscopicity. Previous studies show a decrease of 78% and 65% for ultrafine and accumulation-mode particles, respectively, before and after fog formation [271,272]. This proves the effective scavenging impact of fog on air pollutants and its beneficial effect in washing and cleaning the atmosphere. Fog scavenging mainly takes place either through nucleation scavenging or impaction scavenging. The latter occurs when the interstitial particles (non-activated particles) are incorporated into fog droplets by collision with a droplet, with possible collection mechanisms like inertial impaction, phonetic effects, and Brownian diffusion. However, the former occurs whenever aerosols acting as CCN are activated to generate fog droplets in a supersaturated atmosphere. This pathway mainly dominates in fog aerosol scavenging [259,273]. The scavenging efficiency of different species varies between different chemical species and mainly depends on their water solubility. Studies reveal that fog scavenging removes more water-soluble inorganic components than organic matter [185]. Lower efficiency is observed for carbonaceous hydrophobic species like EC or BC, and higher efficiency is observed for water-soluble species such as SNA [185,266,273]. For instance, the highest scavenging efficiency is observed for nitrate, while that of sulfate is lower [273]. The overall mass scavenging efficiency (MSE), defined as the fraction of PM (expressed as mass concentrations) incorporated into droplets, is a function of particle size and composition and further depends on other conditions (e.g., peak supersaturation, particle number concentration) within the fog. In fogs, two methods can be used to measure the MSE. In the first method, MSE is evaluated from the difference in chemical composition in fog water and interstitial aerosol reservoirs by performing a parallel sampling during foggy events [142,265,274–276]. In the second method, MSE is calculated from the difference in aerosol concentration pre- and post-fog. The scavenging ratio differs from one species to another. Species having higher hygroscopicity and low vapor pressure tend to have higher MSE [142,273,277]. During atmospheric transport, oxidation processes increase the hydrophilic properties of the particles, while coagulation and condensation processes increase particle size. Both

processes are able to ameliorate the scavenging efficiency of aged fog compared to fresh particles, particularly in the case of EC which tends to be hydrophobic and small in size when originally formed. For instance, highly polluted areas with fresher soot are more likely to have lower EC scavenging efficiency, while more aged material will be highly scavenged [22]. Further, there is a relation between the scavenging efficiency and solubility of organic compounds. The efficiency of molecular markers of vehicle exhaust is lower than that of biomass burning, suggesting differences in the fog processing of carbonaceous species released by different source types. Scavenging efficiencies have implications for the atmospheric lifetimes of species released due to the fact that fog processing of fine particles is an important link to the removal mechanisms by occult and wet deposition [276,278]. Regarding gas-phase scavenging, compounds with effective Henry's constants larger than 1000 M atm^{-1} are highly subjected to scavenging and wet deposition. Even in compounds with effective Henry's constants lower than 1000 M atm^{-1}, surface adsorption on the fog droplet may enhance species uptake and contribute to wet deposition due to the large specific surface area contributed to small droplets [266].

8.1.4. Fog Deposition

Wet deposition is the process in which particles and gases are removed from the atmosphere by their impaction on the earth's surface (fog water) or by their absorption into droplets followed by droplet precipitation (rainfall). Wet deposition steadily decreases the atmospheric pollutant loadings in fog droplets during a foggy event. However, the uptake through evaporative water loss upon fog dissipation causes an increase in the pollutant concentrations in the atmosphere. Most fog droplets evaporate before being deposited, altering the chemical and physical properties of the residual particles. These particles become more active, acting as future CCN and promoting future fog formation. This cycle is termed the smog–fog–smog cycle [279]. The importance of the removal process depends on the frequency of occurrence of fog, its duration, and the scavenging efficiency [280]. Fog droplets can be deposited though gravitational settling or turbulent deposition much faster than fine particles are deposited through dry deposition processes. These processes are highly important when fog is in contact with the surface. Fog deposition is equivalent to or even larger than wet deposition fluxes via rain or snow due to the higher solute concentrations [22,154].

8.2. Literature Studies

Several studies concerning the chemical composition have been carried out on fog water in different countries worldwide such as France, Germany, China, Japan, India, and the US [22]. Most of them are directed toward the inorganic fog analysis, while few of them focus on the organic analysis. In the 1980s and 1990s, observational studies of fog chemistry were mostly made in North America and Europe, with few studies in Japan and Asia. Limited studies were performed on the organic analysis (pesticides, PCBs, PAHs, and phenols), especially those in California [281,282], Dübendorf [283], Zürich [284], Strasbourg [285], Colmar [262], North East Bavaria [286], Northwestern Mountains [287], Shanghai [288], and Mount Taishan [289]. One of the most recent publications related to the analysis of organic contaminants of different functional groups in fog water is illustrated in Khoury et al. [18]. In this study, a new analytical approach is developed and optimized for the extraction and analysis of 242 organic compounds of different functional groups (acids, pesticides, PAHs, PCBs, and phenols) and then validated on different fog samples taken from the Alsace region (Erstein, Bas-Rhin) and Fnaideq (Akkar, North-Lebanon). Studies performed on the inorganic analysis of fog water are many including California, Dubendorf, Corvallis, Po Valley, Mount Tremblant, New Delhi, Louisiana, San Joaquin, Strasbourg, etc. [16,285,290–294]. Since 2005, there has been a strong focus on chemistry in Asia, particularly in China [3,176,295–300], Japan [274,275,301,302], India [276,303,304], South Korea [305], and Taiwan [306]. Some observations were reported in Europe from the Czech Republic [307,308] and Poland [158,309]. At the same time, large field studies were

conducted in Germany to investigate the fog and cloud processing of both inorganic and organic pollutants [310–312]. Other locations include Puy de Dome in France [313] and the Po Valley in Italy [314]. In North America, the study of fog chemistry continued in the Central Valley of California [13,14,277,282], northern Arizona [315], the Texas-Louisiana Gulf coast [155,316,317], and the Central California coast [318]. A few studies reported observations in South America [20,319] and Africa [320]. Then, investigators began to examine temporal changes in fog chemistry in several locations [158,274,309,321–325]. Also, a field study on the influence of LRT of air masses on fog water composition was performed in 2019 at the Lumbini site in Nepal. Recently, more studies on the inorganic analysis have been conducted in several locations in India [326], Egypt [222], Switzerland [327], Bangladesh [328], and Lebanon [329].

9. Conclusions

The objective of the current review is to provide the reader with a wide overview of the physical and chemical aspects of fog water. It highlights the different fog types and collectors, the activation process, forecasting and frequency, and the effects of cloud condensation nuclei (CCN), along with its negative and positive impacts on human life and the environment. Fog is a climatic phenomenon impacting the ecosystem, human health, transportation, air quality, and environment balance. It is mainly influenced by the presence of favorable weather conditions (humidity, temperature, boundary layer, wind speed, air masses, etc.) along with the presence of pollution particles (CCN) that are critical to its formation and maintenance. CCN either help in fog formation (increasing the cooling rate) or lead to fog dissipation (decreasing the cooling rate) depending on their behavior. On one side, fog negatively affects a wide variety of human activities due to the reduced visibility (below 1 Km), leading to serious injuries and even deaths in some cases. On the other side, fog has been found to be an important source of fresh water to overcome water scarcity and in agricultural activities and the ecosystem by decreasing pollutant concentrations. The number of research studies related to fog harvesting has increased over time, especially in poor countries that suffer from water shortages. This is particularly vital for poor regions where the water distribution infrastructure is inaccessible or poorly designed because of inadequate rules and regulations by local governments. However, additional technical work is still needed to advance the physical development of this sustainable technology in order to find the optimal mesh type and structure (2D/ 3D) to maximize the water yield. Fog chemistry has been widely studied for a long time and has expanded recently to cover more countries. Most of the studies focus on the inorganic composition of fog water, whereas few of them investigate the organic matter. Its chemistry is a function of the droplet size which varies from case to case depending on the rate of the gas uptake, rate of the CCN condensation, rate of the chemical reactions, etc. The fog droplet is composed of a mixture of organic and inorganic species, resulting from the scavenging of those particles. The particle scavenging efficiency mainly depends on its solubility (the degree of hygroscopicity) and vapor pressure. The main fractions that are found in fog water include organic and inorganic carbon, Humic-like substances (HULIS), and more recently bacteria. Fog droplets are found to be an effective medium for microbial sustenance and transport. More research should be performed on the analysis of fog biology (bacteria, fungi, etc.) because of the limited number of papers regarding this issue. It is also necessary to work more on developing new analytical protocols for the characterization of a wide number of organic and biological contaminations in fog water. Furthermore, fog acts like a reservoir where aqueous-phase reactions occur. Those reactions accumulate the oxidized species which either increase or decrease the particle loadings after the foggy events. This phenomenon leads to the loss of the species through the wet deposition or the formation of new particles to promote future foggy events. Lots of studies have achieved notable improvements in understanding the chemistry, mechanism, and nature of fog. However, further studies are required to elaborate on the evolution of each fog type according to the different phases (formation, maturation, and dissipation). Moreover, a wide number of

studies have shown a decrease in fog frequency worldwide since 1980. The investigations revealed two main reasons responsible for this decrease: either an improvement in air quality (especially a decrease in sulfur dioxide) or an increase in the air temperature (caused by the urban heat island). Fog modeling algorithms such as numerical weather prediction (NWP) and artificial intelligence have helped to forecast fog. However, its prediction is still incomplete given the intrinsic uncertainty in the initial conditions and physical parameters. Thus, new models and techniques can provide more accuracy for fog forecasting. By gathering all the information regarding the physical (life cycle, activation process, aerosol impacts, etc.) and chemical (composition, chemical reactions, etc.) aspects of fog, further achievements can be performed to better understand its evolution with time. Regarding fog collection, it will be practical to add a feature for the active fog collectors to be operated remotely by connecting them to a cellphone or smartwatch via Bluetooth. In spite of the abundant study of this issue so far, it is still an open field for continuous development and research.

Author Contributions: D.K. wrote the original manuscript. M.M., Y.J. and O.D. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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