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Review

Viability of Artificial Rain for Air Pollution Control: Insights from Natural Rains and Roadside Sprinkling

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Abstract: Artificial rain, a technology primarily used for drought relief, has recently been used for combating regional air pollution. However, there are limited available measurement data to confirm the effectiveness of this control practice. In this study, we summarize control theories and indirect but relevant observations/findings, including air pollutant reduction after natural rain events and roadside sprinkling. A brief review of artificial rain basics is also provided. Our work shows that artificial rain appears to be a promising management strategy for air pollution control. However, field measurements are needed to further assess the cost-effectiveness of the practice, as well as the other benefits or challenges it may create.

Keywords: cloud seeding; artificial rain; air pollution; wet deposition; roadside sprinkling

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1. Introduction

Air pollution poses a serious environmental challenge to countries undergoing rapid industrialization and urbanization. It adversely affects community health and well-being. According to a recent study in India, air pollution caused 1.67 million deaths in 2019 [1]. In addition to health impacts, degraded air quality also results in reduced crop yields, impaired visibility, structure weathering, soil/water acidification, etc., causing substantial economic and social consequences [2]. Various technologies and management practices have been developed to combat air pollution. These include but are not limited to source reduction (e.g., using low-sulfur fuels), recycling (e.g., exhaust gas recirculation), end-of-pipe treatment (e.g., electrostatic precipitators for dust removal), and controlled discharge (e.g., using a high chimney to enhance air dilution) [3,4]. However, we have limited tools for removing air pollutants already in the ambient air.

Artificial rain has recently been discussed and implemented for the mitigation of existing ambient air pollution. Examples in the popular press include the following: (1) "Can artificial rain help curb air pollution" [5], (2) "South Korea and China are using artificial rain to 'wash away' air pollution" [6], "Delhi's overall air quality 'very poor', artificial rain may be induced" [7], and (3) "China 'modified' the weather to create clear skies for political celebration—study" [8]. While gaining visibility in the popular press, there is a scarcity of peer-reviewed research supporting or refuting the effectiveness of artificial rain for air pollution control. A recent study conducted in Korea stands out as the only one, and it reported slightly reduced PM_{10} concentrations following two artificial rain events [9,10]. To address this gap and stimulate further research, this paper reviewed control theories behind this technology and indirect but relevant observations/findings, including air pollutant reduction after natural rain episodes and roadside sprinkling. It is important to note that drought relief and hail reduction are typically the primary objectives of artificial rain, with air pollution control as a potential side benefit [11]. However, with increasing public awareness of air quality, air pollution control may become a primary objective when planning for artificial rain efforts.

2. Methodology

The literature search followed the PRISMA methodology, encompassing four steps: identification, screening, eligibility, and inclusion. Given the diverse scope of this review, separate efforts were made on each of the four subjects: artificial rain basics, control theories, pollution reduction via natural rainfall, and roadside sprinklers. For the first two subjects, the focus was on classic books and peer-reviewed journal articles in the pertinent fields, without an exhaustive literature research. In contrast, for the last two subjects, the literature search aimed to include all relevant publications from the past 20 years (2003–present). The search began with articles indexed by three databases: EBSCO, Scopus, and Web of Science. To maximize search records, the references of each identified article from the three databases, as well as publications citing the identified articles (based on Google Scholar), were examined to assess their relevance. The complied search records were subsequently screened based on uniqueness (excluding duplicate records), relevance (eliminating less relevant ones), originality (including only original studies), and language (limited to English or Chinese). The remaining records underwent an eligibility assessment based on full text accessibility, relevance, and scientific soundness. A summary of the literature search process is given in Table 1. A total of 91 publications were included, with an additional 27 referenced to support relevant discussions.

Table 1. Literature search procedure adopted for this study.

Literature Search Procedures		**Artificial Rain Basics**	**Control Theories**	**Pollutant Reduction by Natural Rainfall**	**Roadside Sprinklers**
Keywords (search terms)		(Cloud seeding ∣ artificial rain ∣ rainmaking) and (agent ∣ cloud condensation nuclei ∣ cost)	(Wet deposition ∣ below-cloud precipitation scavenge) and (collision ∣ absorption ∣ source suppression)	(Wet deposition ∣ below-cloud precipitation scavenge) and (reduction efficiency ∣ removal efficiency) and (air pollutant)	(Roadside sprinkler ∣ artificial rain) and (reduction efficiency ∣ removal efficiency) and (air pollutant)
Identification	Records identified from the four databases and others	1241	845	338	67
Screening	Records after eliminating duplicates	662	587	266	53
	Records remaining after other screening	228	191	107	28
Eligibility	Records with full text available	93	64	47	19
	Records remaining after eligibility assessment	27	24	26	14

Table 1. *Cont.*

Literature Search Procedures		Artificial Rain Basics	Control Theories	Pollutant Reduction by Natural Rainfall	Roadside Sprinklers
Inclusion	Full-text publications included in the review	27	24	26	14

3. Artificial Rain Background

The concept of artificial rain was initially proposed in 1946 by Vincent Schaefer and Bernard Vonnegut [12]. Since then, it has expanded into a broader set of weather modification approaches that aim to achieve objectives that require certain weather conditions, such as timely rain for crops [13]. According to the World Meteorological Organization (WMO), 42 countries had weather modification programs in 2013, while 56 countries utilized artificial rain in 2016. Among them, China had the largest program, followed by the United States, Thailand, and India [14]. Most weather modification programs focus on precipitation enhancement and hail mitigation [15].

Atmospheric water vapors originate primarily from evaporation at the Earth's surface and rise to the upper troposphere and lower stratosphere via orographic lifting, convergent lifting, convective lifting, and frontal lifting [16]. At high altitudes where the air temperature is lower than the dew point, cloud drops and ice crystals form through nucleation [17] and further grow in size into raindrops or snowdrops [18]. Factors that alter any of these processes, individually or collectively, can be utilized to create artificial precipitation [19].

Aerosols play a key role in cloud formation by acting as cloud condensation nuclei (CCNs) [20]. Artificial rains can be created by spreading aerosols in clouds, known as cloud seeding. Three steps are typically involved. First, supersaturated water vapors condense on the surface of the clouds and spread aerosols to initiate the formation of cloud drops. Secondly, condensation is increased by factors such as latent heat and hygroscopicity, which are tied to the physical and chemical properties of the aerosols. Finally, raindrops are formed from cloud drops through processes such as collision and coalescence [21]. A water droplet starts to fall when its downward gravitational force is larger than the updraft of buoyant air [22]. Depending on the target cloud type, cloud seeding can be categorized into:

- Glaciogenic seeding. In cold clouds (usually residing at high altitudes), water freezes around particles to form ice crystals. Seeding supercooled clouds adds more nuclei. As the ice crystals grow in size, they fall and melt as they go, turning into raindrops.
- Hygroscopic seeding. It targets warm clouds (usually occurring at lower altitudes). The purpose is to encourage the coalescence of cloud drops by providing large nuclei or droplets.

For cold clouds containing supercooled liquid water (<0 °C), typical seeding agents include AgI, KI, PbI_2, dry ice, and liquid propane (which absorbs considerable heat upon expansion into a gas) [23]. Introducing dry ice can produce ice crystals. These crystals subsequently grow through vapor deposition, riming, and aggregation to particles large enough to create precipitation [24,25]. With a similar crystalline structure to ice, AgI helps induce water freezing and acts as an effective nucleant for ice crystal formation.

Warm clouds or fogs are usually seeded by hygroscopic agents such as NaCl, NH_4Cl, and urea particles. Upon being injected into clouds, salt particles of ~5–20 microns grow rapidly to 40–100 microns. Precipitation occurs when these large particles collide and merge with smaller cloud drops. An effective agent should maintain its affinity for water vapors even at low aqueous concentrations—the agent concentration decreases as particles grow due to water condensation [26]. Hygroscopic salts generally lack the same multiplying effect as AgI in terms of raindrop creation [27]. To address this issue, a chain reaction process was invented to increase the seeding effectiveness [28].

Cloud seeding can also be classified into aerial and ground rainmaking, which is dependent on the point of agent release [29]:

- Ground rainmaking uses ground-based generators (GBGs) or canisters fired from anti-aircraft guns or rockets to dispense seeding agents. A GBG is usually deployed in mountain areas, with a burner constituting its central component. A burner can, for example, nebulizes an AgI-acetone solution to create AgI aerosols, and the released AgI aerosols then rise into the clouds. Both manual and remotely controlled GBGs are available [30].
- Aerial rainmaking uses aircraft to dispense seeding agents to the bases or tops of clouds. Top seeding injects seeding agents to the top of a supercooled cloud, while base seeding discharges the agents in the updraft region of a cloud base [31]. Aerial cloud seeding is the most prevalent method for dropping CCNs [32]. CCNs can be placed in flares and loaded onto an aircraft. An aircraft can also carry cylinders containing seeding agents and release them into the cloud [33].

In general, GBGs are effective for cloud systems, with most available moisture staying close to the ground, whereas aircraft systems are effective for clouds with moisture mostly available at high altitudes [34]. In some cases, the moisture zone within a cloud can extend from near the ground to at or above combat levels, allowing the use of both ground and aerial seeding [29]. Ground rainmaking with GBGs is typically less expensive than aerial rainmaking [35].

The cost of cloud seeding varies depending on factors such as countries and locations, cloud conditions, and the selected technology. In North Dakota, USA, aerial rainmaking costs an average of USD 98.84 per km^2 [36]. With that, a 10% enhancement in rainfall during the growing season is anticipated as the weather modification program primarily focuses on drought relief. A comparable cost rate (USD 91.43 per km^2) was reported by the Royal Rainmaking Project in Thailand [37]. Therefore, cost does not appear to be a limiting factor when applying artificial rain for air pollution control.

4. Control Theories

Wet deposition and depletion. The scavenging removal of air pollutants from the atmosphere during precipitation is known as wet deposition. Another relevant process is wet depletion, which refers to the removal of air pollutants from a source pollutant plume during precipitation. Both can reduce ground-level air pollutant concentrations [38]. According to the location of occurrence, wet deposition can be further classified into rainout (in cloud) and washout (below cloud) [39]. The latter, also known as below-cloud precipitation scavenging, is more relevant to air pollution control. The interactions between raindrops with gas and particulate pollutants have been long recognized and extensively studied [40–42]. Different theories or models may use different sets of equations to describe wet deposition and depletion processes. For example, in AERMOD (a regulatory air dispersion model adopted by the United States Environmental Protection Agency), the wet deposition flux for PM (F_{wp}), which characterizes the PM removal per unit of time per unit of ground surface area, is proportional to column average PM concentration (ρ_p; averaged vertically from the ground to the mixing height), precipitation rate (r; also known as intensity), and PM washout coefficient (W_p). W_p can be calculated as [43]:

$$W_p = \frac{3z_p E}{2D_m} \tag{1}$$

where z_p is the mixing height, D_m is the mean diameter of raindrops, and E is the collision efficiency; it is a function of precipitation fall speed, PM size, raindrop size, etc. In the same model, the wet deposition flux for gases (F_{wg}) is proportional to the pollutant concentration in the raindrop (C_l), molecular weight of pollutant (M_w), and precipitation rate (r). C_l

is a function of Henry's constant of a gas, precipitation rate, and the residence time of raindrops in the mixing height. Despite mathematical complexity, for both PM and gases, wet deposition fluxes generally increase with the precipitation rate and the concentration of a pollutant [44]. Similar to AERMOD, CMAQ, a prevalent photochemical air quality model, also parameterizes wet deposition as a first-order kinetic process, with the deposition rate/flux proportional to the precipitation rate [45].

Collision/coagulation. Microscopically, the collision of PM with water droplets can be described by Brownian or kinematic collision processes. The Brownian collision process is pronounced when both the PM and droplets are smaller than a few microns, and thus their movement is dominated by Brownian motion [46]. This applies to PM but not to raindrops with typical diameters of a few millimeters. Since PM is smaller than raindrops, the mixing of PM and raindrops is considered polydispersed. For polydisperse collision, the Brownian collision coefficient, $K(D_p, \widetilde{D}_p)$ increases with the size of droplets. Kinematical collision is a process driven by the relative motion between particles (Note: PM and droplets are both considered as particles in physics) [47]. In rainfall, the relative motion and interaction between PM and raindrops is primarily caused by gravitational forces (also known as gravitational collision). The removal of PM by droplets can be described as [47]:

$$C_{pn}(t) = C_{pn0} \exp\left(-\frac{\pi}{4} d_d^2 V_r C_{dn} K_c t\right) \tag{2}$$

where $C_{pn}(t)$ is the pollutant concentration at time t, C_{pn0} is the initial pollutant concentration, d_d is the diameter of droplets, V_r is the relative velocity of droplets to particles, C_{dn} is the droplet concentration, and K_c is the PM capture efficiency of droplets. (Note: This equation is the integration form of the inertia collision equation in Ref. [46]). K_c can be estimated as follows:

$$K_c = \left(\frac{Stk_c}{Stk_c + 0.12}\right)^2 \tag{3}$$

This equation only applies when the Stokes number for PM capture (Stk_c) is greater than 0.1 and Stk_c can be calculated as:

$$Stk_c = \frac{\rho_p d_p^2 C_c V_r}{18\eta d_d}_c \tag{4}$$

where ρ_p is the density of PM, d_p is the diameter of PM, C_c is the slip factor of PM, and η is the air viscosity. According to Andronache [48], for coarse PM with a diameter greater than 2 µm (coarse mode), its wet deposition is largely attributed to kinematical collisions; while for ultra-small PM smaller than 0.01 µm (Aitken mode), Brownian collision becomes predominant. A relatively low collision efficiency and accordingly low PM removal are associated with PM of 0.1–1 µm (accumulation mode), especially under low-to-moderate-intensity rainfall conditions (0.1–10 mm/h). A similar simulation result was obtained by Bae et al. [49].

Absorption. The absorption equilibrium of a gas pollutant into raindrops is determined by its water solubility and Henry's constant (H). Thus, the two parameters have significant implications for pollutant removal via rainfall. For example, Zeri et al. [50] reported that while rainfall could effectively reduce ambient SO_2 concentrations (by 40%), rainfall was ineffective for CO removal. These researchers attributed the difference in effectiveness to the low solubility of CO in water and relatively higher solubility of SO_2 (0.0026 g per 100 mL at 20 °C; versus 9.6 g per 100 mL for SO_2). Gases like NH_3 and SO_2 react with water after being absorbed, and thus demonstrate high solubility and H values. For nonreactive gases, the absorption rate of a pollutant is governed by its mass transfer at the air–water interface, which can be described by the classic two-film theory. For reactive gases, the absorption rate is further affected by chemical reaction kinetics [41]. Depending on precipitation, pollution, and environmental conditions, the absorption process can be limited by gas-phase diffusion, liquid-phase diffusion, chemical reactions, etc. Thus, an equilibrium may not have been reached when raindrops touch the ground. For some gas pollutants (e.g., semi-volatile organic compounds), in addition to gas absorption into raindrops, they can be washed out in particulate forms through gas–particle partitioning. Multiple processes can be involved in gas–particle partitioning, including absorption (e.g., to particle-bonded water or oil), adsorption, phase change (e.g., condensation), and chemical reactions [51,52].

Source suppression. Water application/spray has been extensively practiced to suppress the suspension and resuspension of fugitive dust (e.g., mine and road dust) [53]. Salts (e.g., $MgCl_2$) and synthetic polymers are often added to improve dust suppression effectiveness. Dust suppression via water spray is governed by two mechanisms: agglomeration and hygroscopicity. Agglomeration is a process of binding dirt particles together or to other solid particles to create larger particles that are less prone to suspension. It often occurs on the top surface of soil or dirt where the large particles or crusts create a protective layer preventing small particles underneath from airborne suspension. Hygroscopicity represents the size growth of dirt particles due to the sorption of moisture from the surroundings. Sorption can be a chemical or physical process or a combination of both [54]. Wettability is an important parameter affecting particles' hygroscopic growth as well as agglomeration, and it can be adjusted by adding chemicals (e.g., salts and polymers) to water to be sprayed. For artificial rains, the water received on the ground is predominantly pure water, but dust suppression through agglomeration and hygroscopicity likely still occurs. Compared to PM, the effect of rainfall on the generation of other air pollutants remains understudied and depends on the type of sources and air pollutants. For example, a wet soil condition can encourage the anaerobic decomposition of biomass, leading to elevated H_2S and CH_4 concentrations [55] and certain fungi tend to release spores on rainy days [56].

Simulation models. Numerous models are available to simulate the wet deposition (below-cloud precipitation scavenging) process [57–59]. Specifically for artificial rains, a research group in India developed a stochastic nonlinear mathematical model to simulate the removal of air pollutants [60,61]. Two major findings were derived from their simulation study. First, an increase in the rate of water vapor formation decreases the concentration of air pollutants in the atmosphere. Secondly, as the interaction of raindrops with air pollutants increases, the equilibrium concentration of the pollutants decreases. The authors claimed that the model can be used to quantify the maximum allowed emission rate of PM to ensure compliance with air quality standards. It should be noted that the model formulation did not fully adopt the classic wet deposition/depletion or collision theories. Caution should be taken when interpreting the modeling results.

5. Pollution Reduction Using Natural Rainfall—Indirect Evidence

While few field trials have been conducted to confirm the effective reduction in air pollution with artificial rain, studies of natural rainfall indicate an effective reduction in air pollution. Table 2 summarizes existing studies concerning the impacts of natural rainfall on various air pollutants in the past 20 years. The majority of studies feature an analysis of long-term air quality and meteorological data to reveal the impact of wet seasons (i.e., elevated precipitation) on air pollutants [62–64], while a few studies focus on air pollutant concentrations before, during, and after precipitation events, e.g., Refs. [65,66]. Numerous notable efforts have been made to determine the wet deposition flux of air pollutants [57,67–69]. However, as stated in Section 4, the overall reduction in air pollution is attributed to not only wet deposition but also other processes such as source suppression. Thus, pure wet deposition studies are not included in this review, even though many of these studies indicate a potentially significant role of wet deposition in air pollutant removal.

Table 2. Reduction in atmospheric air pollutants after natural precipitation—A summary of observations since 2003 in chronological order.

References	Pollutants	Reduction Efficiency	Type of Environment	Location	Key Findings and Notes
[70]	SO_2, NO_2, and total suspended particles (TSP)	38% for SO_2 44% for NO_2 40–48% for TSP	Industrial area	Delhi, India	Reduction efficiency (%) was determined from the field measurement of air pollutants before and after rainfall.
[71]	PM_1 and associated organic matter (OM)	n/a	Urban	Princeton, NJ, USA	PM_1 and OM concentrations decreased immediately after each rain event (a total of ten). A scavenging coefficient was related to PM size and chemical composition.
[63]	$PM_{2.5}$	n/a	Mostly urban	USA	The study analyzed $PM_{2.5}$ and meteorological data collected from 1998 to 2008 and found a significantly negative correlation between $PM_{2.5}$ concentration and precipitation rate in most areas of the United States.
[50]	PM_{10}, SO_2 and CO	30% for PM_{10} 40% for SO_2 No significant reduction in CO	Urban	Rio de Janeiro, Brazil	Reduction efficiency (%) was determined through a statistical analysis of long-term air quality and meteorological data. Rainfall was not effective in CO removal, likely due to the low solubility of CO in water (0.0026 g/100 mL at 20 °C).
[62]	PM_{10}, SO_2, NO_2, CO, and O_3	% of grids with a significant negative correlation with rainfalls in Period 1: 83% for PM_{10} 65% for SO_2 42% for NO_2 41% for CO 12% for O_3 In Period 2: 51% for PM_{10} 31% for SO_2 31% for NO_2 18% for CO 3% for O_3	Urban and rural	Seoul, Korea	The study compared long-term air quality and meteorological data in 83 gridded areas. A case study on two convective rain events revealed increased NO_2 and O_3 concentrations during rainfall, likely due to lightning-caused NO_2 formation and the downward transport of O_3 from the O_3 layer to the surface.
[72]	$PM_{2.5}$	n/a	Urban	Haidian District, Beijing, China	A strong negative correlation (R^2 = 0.668–0.974) was found between the amount of cumulative rainfall and $PM_{2.5}$ concentration.
[73]	PM	n/a	Urban	Lanzhou, China	Six rain and three snow events were studied. PM number concentrations were generally lower during the events than before and after. Rainfall more effectively reduced coarse PM compared to fine PM.
[74]	$PM_{2.5}$	% of rain events resulting in PM reduction: 52% with light rain (<2.5 mm/h) 71% with moderate rain (2.6–8.0) mm/h) 77% with heavy rain ($\geq$8.1 mm/h)	Urban	Haidian District, Beijing, China	A theoretical discussion based on PM's Stokes numbers revealed little effect on the reduction in rainfall on PM < 2 μm, while it had a greater effect on PM > 2 μm.

Table 2. *Cont.*

References	Pollutants	Reduction Efficiency	Type of Environment	Location	Key Findings and Notes
[75]	$PM_{2.5}$, PM_1, SO_2, NO_2, O_3 and PM_1 components (OM, NO_3^-, SO_4^{2-}, NH_4^+, Cl^-)	45–97% for $PM_{2.5}$ 41–93% for PM_1 2–66% for SO_2 5–77% for $NO_3$63 –92% for O_3	Urban	Chaoyang District, Beijing, China	The study focused on an extreme precipitation event (326 mm) and pollutant reduction before, during, and after the event. Soluble ions were reduced at a greater ratio than SO_2 and NO_2.
[76]	PM_{10}, $PM_{2.5}$, SO_2, NO_2, and O_3	6.2% for PM_{10} with 5–10 h rainfall 50.7% for NO_2 with 10–15 h rainfall 59.8% for SO_2 with 15–20 h rainfall	Urban	Shapingba District, Chongqing, China	Little reduction was found with summer rainfall <5 mm. Pollutant reduction increased with the amount of rainfall. Longer rainfall durations promoted SO_2 and NO_2 reduction but had no similar effect on PM_{10} and $PM_{2.5}$.
[65]	SO_4^-, NO_3^-, and NH_4^+ in $PM_{2.5}$	56% for SO_4^- 61% for NO_3^- 47% for NH_4^+	Urban	Beijing, China	The study examined the time series of $PM_{2.5}$-associated SO_4^-, NO_3^-, and NH_4^+ concentrations over three months, including 17 rain events. SO_4^-, NO_3^-, and NH_4^+ concentrations in PM_1 were also measured and they significantly correlated with those in $PM_{2.5}$.
[77]	PM in the size range of 0.1–24 µm	10% during rainfall; 18% after rainfall	Urban	Leon, Spain	A total of 54 rain events were studied. PM reduction was less pronounced for PM of 0.3–1 µm, known as the Greenfield Gap [78]. PM concentrations were negatively correlated with rain intensity.
[79]	$PM_{2.5}$ associated ions (NO_3^-, SO_4^{2-}, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, and Mg^{2+})	n/a	Urban	Beijing, China	$PM_{2.5}$ concentrations were highest during light rain events and decreased by 17–27% as rain intensity increased. Comparing after versus during rain events, Na^+, Ca^{2+} and Mg^{2+} mass concentrations in $PM_{2.5}$ increased, while other ions decreased likely due to soil resuspension.
[80]	$PM_{2.5}$	5.1 ± 25.7% with light rain (0.1–2.5 mm/h) 38.5 ± 29.0% with moderate rain (2.6–7.6 mm/h) 50.6 ± 21.2% with heavy rain (>7.6 mm/h)	Urban	Beijing, China	A total of 117 rain events during the period of 2014–2016 were analyzed. $PM_{2.5}$ reduction efficiency increased with rain intensity. For light rain events, rain duration and wind speed significantly impacted $PM_{2.5}$ reduction, as compared to raindrop size.
[81]	Ultrafine PM (<0.4 µm), superfine PM (0.4–1 µm), and coarse PM (>1 µm)	>75% for all PM size fractions when rain >17 mm/h; >50% for all PM size fractions when rain duration >110 min	Remote	Darjeeling, India	A total of 135 rain events between 2009 and 2018 were studied. PM reduction efficiency generally increased with rain intensity and duration and was higher for coarse PM than ultrafine and superfine PM.

Table 2. *Cont.*

References	Pollutants	Reduction Efficiency	Type of Environment	Location	Key Findings and Notes
[82]	PM_{10} and $PM_{2.5}$	n/a	Urban	Beijing, China	PM data from 12 sites in Beijing from 2015 to 17 were analyzed. Light (<10 mm) short-duration rain events increased $PM_{2.5}$ and PM_{10} concentrations, while heavy rain events led to effective reductions in both. The reason for this was ascribed to aerosol hygroscopic growth and gas–particle conversions.
[83]	$PM_{2.5–10}$ and $PM_{2.5}$	For $PM_{2.5–10}$: 31.7 to 38.4% with drizzle 40.8 to 51.9% with light rain 52.6 to 75.5% with moderate rain 62.8 to 86.3% with heavy rain For $PM_{2.5}$: −36.5 to −16.5% with drizzle 23.9 to 42.9% with light rain 47.1 to 68.5% with moderate rain 59.2 to 68.3% with heavy rain	Urban	Beijing, China	The study examined PM concentration data and precipitation data from 2008 to 2017. Precipitation was more effective at reducing PM_{10} than $PM_{2.5}$. PM reduction efficiency increased with precipitation intensity and duration. PM reduction by precipitation also exhibited seasonality and dependence on precipitation occurrence time (day versus night).
[84]	PM_{10} and $PM_{2.5}$	n/a	Various	Bangladesh	Eleven sites were studied. Both $PM_{2.5}$ and PM_{10} concentrations were negatively correlated with rainfall ($R = -0.59$ and -0.61, respectively).
[64]	$PM_{2.5}$	n/a	Various	Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta, China	In all three regions, $PM_{2.5}$ concentrations were significantly lower on rainy days than on non-rainy days. $PM_{2.5}$ reduction was small or negative when both $PM_{2.5}$ concentrations and precipitation intensity were low.
[85]	PM_1	On average: 15% for nucleation mode (14–30 nm) 4% for Aitken mode (30–100 nm) 22% for accumulation mode 1 (100–300 nm) 21% for accumulation mode 2 (300–1000 nm)	Suburban	Spain	Precipitation intensity strongly affected the scavenging of PM in different size ranges. No or little reduction was found with rain <3 mm/h, especially for PM <100 nm. When rain intensity was > 3 mm/h, the reduction efficiency was 62% for the nucleation mode, 62% for the Aitken mode, 62% for the accumulation mode 1, and 52% for the accumulation mode 2.
[86]	$PM_{2.5}$	n/a	Various	Part of Hunan and Hubei, China	$PM_{2.5}$ concentrations had a significant negative correlation with precipitation intensity during two precipitation periods ($R = -0.57$ and -0.44).

Table 2. *Cont.*

References	Pollutants	Reduction Efficiency	Type of Environment	Location	Key Findings and Notes
[87]	PM_{10}	n/a	Urban	Leon, Spain	In nearly all rain events, PM_{10} concentrations were reduced, and the reduction showed a significant seasonality. Long and continuous rainfall benefitted fine PM removal.
[88]	PM_{10} and $PM_{2.5}$	−8–27% for PM_{10} −2–17% for $PM_{2.5}$	Various	Jiangsu, China	A total of 27,219 precipitation events were analyzed. PM reduction efficiency varied and generally increased with PM concentrations before precipitation and precipitation intensity. A small or negative reduction was noted when PM concentrations were <40 μg/m^3 and rain intensity <1 mm/h.
[89]	$PM_{2.5}$	2.0 ± 38.6% for light precipitation 28.2 ± 34.8% for moderate precipitation26.8 ± 33.7% for heavy precipitation	Urban	Fujisawa, Kanagawa, Japan	Similar findings to Ref. [80] were reported. Lower $PM_{2.5}$ reduction efficiencies than those in Ref. [80] were ascribed to heavier air pollution in Beijing.
[90]	PM in the size range of 0.2–25 μm	n/a	n/a	Jeju Island, Korea	Lower PM number concentrations were observed after precipitation in three out of four rain events.

Among various air pollutants, PM is the most extensively studied (Table 2). The collision process causes the entrapment of PM into raindrops, resulting in reduced PM concentrations near the ground level where human exposure occurs. As described in Section 3, PM size is a key factor affecting the collision coefficient and accordingly PM removal via wet deposition. The size of dust particles (PM) also affects their suspension potency [91]. Soil moisture, which increases with precipitation, exhibits a greater influence on the suspension of large PM than small PM [92]. Several studies leveraged such size-dependency to investigate precipitation-induced PM reduction. They achieved this by comparing the PM size distribution profiles before and after a precipitation event [66,71]. Overall, an effective reduction in PM_{10} concentrations was reported, ranging from 30% [50] to 86% [83], depending on the precipitation characteristics (e.g., rate and type). However, no agreement has yet been reached regarding $PM_{2.5}$ reduction. Tai et al. [63] found that $PM_{2.5}$ concentrations demonstrated a negative correlation with precipitation rates in most regions of the United States, suggesting that rainfall caused a reduction in $PM_{2.5}$. A similar observation was made in Beijing, China [72,75]. In another study in Beijing, Xu et al. [65] reported that $PM_{2.5}$ concentrations were significantly lower (by ~30%) during rainy days than on non-rainy days. However, Dong et al. [74] observed an insignificant correlation between $PM_{2.5}$ concentrations and precipitation rates in the Haidian District, Beijing, China. In 43.2% of the precipitation events, $PM_{2.5}$ concentrations increased. The poor $PM_{2.5}$ reduction effectiveness could be explained by the relatively low collision efficiency of cumulative-mode PM (0.1–1 μm) with raindrops [48]. This size fraction of PM can contribute significantly to atmospheric $PM_{2.5}$ in Beijing [93]. Zheng et al. further classified the precipitation in Beijing into drizzle (<0.1 mm), light rain, moderate rain, and heavy rain, and found that while the latter three led to an effective reduction, $PM_{2.5}$ concentrations increased after drizzle [83]. The authors ascribed the negative $PM_{2.5}$ removal to the small raindrop size of drizzle and, accordingly, a low relative velocity (V_r). Other than size, the chemical composition of PM is anticipated to affect its interaction with water (including liquid and vapor) and, accordingly, its entrapment into raindrops and suspension/resuspension potency. However, this effect is complex due to the variability in size among PM particles with distinct chemical compositions. Thus, it is difficult to delineate the effect of PM size and chemical composition even though a few studies reported the preferential reduction in PM of certain chemical compositions [66,71,75].

Precipitation characteristics also substantially influence PM reduction effectiveness. The first influential characteristic is precipitation intensity. Zheng et al. [83] found that for both $PM_{2.5}$ and $PM_{2.5–10}$, their reduction efficiency increased with precipitation intensity. This is consistent with the simulation results acquired by Refs. [48,49]. In reality, a linear relationship of wet deposition flux with precipitation intensity has been assumed for many air quality models, such as CMAQ [45]. A pertaining characteristic is raindrop size, which generally increases with precipitation intensity [49]. Zheng et al. [83] attributed elevated $PM_{2.5}$ concentrations observed after drizzle to its small raindrop size. However, Mircea et al. [94] found no significant effect of raindrop size on the PM scavenging coefficient for rain events with intensity <50 mm/h. A similar finding that raindrop size exhibited little effect on $PM_{2.5}$ reduction under light rain conditions was reported in Ref. [80]. Another influential factor is precipitation duration. Long-duration rains were found to result in increased PM reduction [45,83]. The interaction between precipitation intensity and duration, however, exhibited a complex pattern. Short-duration heavy rains were found to be effective in reducing PM < 2.2 μm, while long-duration light rains were more effective for PM > 2.2 μm [45]. However, Ref. [73] reported that long-duration light rains were effective in reducing PM of 10–50 nm. In addition to its effect on accumulative wet deposition, precipitation duration may substantially affect soil moisture. High soil moisture levels caused by long-duration rains would suppress the suspension of fugitive dust, leading to an effective reduction in coarse PM. This may explain the extended PM removal durations (the period during which effective PM reduction is sustained) after long-duration rains observed in Ref. [83]. Other influential characteristics include precipitation frequency [95], type (stable versus convective precipitation) [96], occurrence time (daytime versus nighttime), and season [83,97]. However, due to limited data, no summarization was attempted here.

In contrast to PM, fewer studies were conducted on the reduction in gas pollutants caused by natural rainfall. For reactive gases with moderate solubility, like SO_2 and NO_2, a relatively high reduction efficiency was reported [50,70,75] while for CO with low solubility, no significant reduction was observed [50]. This aligns with the theory and equations employed in AERMOD and other air quality models. A potentially positive effect of rainfall on CO reduction was suggested by Yoo et al. [62]. However, it is important to note that this effect was measured in the study using the percentage of grids in which a significant negative correlation of CO concentrations with precipitation rates occurred. Possible confounding variables were not considered, such as reduced CO emissions during rainy days due to less traffic. Although no studies have explicitly discussed the subject, the effects of rainfall on primary and secondary air pollutants are anticipated to be different. Wet depletion can contribute significantly to the reduction in primary air pollutants, such as SO_2 and NO, by washing them out from the source plume. Secondary air pollutants are formed from physical and chemical transformations in the atmosphere. Thus, the effect of rainfall can be complicated by other meteorological factors that affect the formation and transport of these pollutants. For example, Yoo et al. [62] observed increased O_3 concentrations during two convective rain events and ascribed these to the transport of O_3 from the lower stratosphere/upper troposphere to the surface. No attempt was made here to summarize the impact of precipitation intensity and duration on the reduction in gas pollutants due to limited information available in the literature.

6. Roadside Sprinklers—An Analogy

The primary purpose of a roadside sprinkler (either stationary or mobile) is to control the PM of road dust origins. Road dust is a key PM source in metropolitan areas, and it can account for up to ~26% of ambient $PM_{2.5}$ and PM_{10}, depending on locations and meteorological conditions [98]. Roadside sprinklers are used in several megacities in China to combat air pollution, and a significant reduction in $PM_{2.5}$ concentrations has been noted through field monitoring [99]. In another study, an automated roadside sprinkling system was developed to suppress dust suspension and mitigate ambient PM, and it achieved a 95–100% reduction efficiency [100]. A sprinkler can be used to achieve other objectives too. For example, it was used to generate fresh or salty water mist for the inactivation of airborne influenza viruses in winter, as the survivability of the viruses decreased with absolute humidity [100]. It was also used to spray salty water in winter to de-ice and de-snow roads, and a mist in summer to cool down the air [101].

During sprinkling, fine water droplets were dispensed into a PM plume. Airborne particles were scavenged by water droplets through Brownian and kinematic collisions and precipitated out due to gravity [102]. Sprinkling is particularly efficient in removing fugitive dust with large-sized particles, since the Stokes number for particle capture (Stk_c, in Equation (4)) and, accordingly, particle capture efficiency (K_c, in Equation (3)) increases with PM size (d_p). The efficiency of a sprinkler system is related to the probability of collision between PM and water droplets. When these two are of similar size, there is a greater chance of collision, and therefore particle removal [103].

Various water-spraying technologies were tested and compared for air pollution control. Based on the initial velocity of droplets, they can be classified into (1) high-velocity (9–15 m/s) sprinklers, generating small-to-medium droplets, and (2) low-velocity sprinklers (1–5 m/s), generating medium-to-large droplets. Many of the tested systems generated relatively large water droplets (>250 μm). To produce small droplets, specialized nozzles are required. For example, hydraulic nozzles can produce droplets as small as 90–100 μm when operating at a pressure of ~5–6 bar. However, it is difficult to lower the droplet size to <30 μm [104,105]. A sprinkler can have multiple adjustable nozzles to generate streams with variable flow rates, coverage, height, and directions [106].

Based on operating pressure, roadside sprinklers can be classified into high-pressure and low-pressure systems. The former was found to deliver a better PM mitigation performance due to the smaller water droplets produced. For example, ~99.1% of PM removal was achieved in a recent study using high-pressure water nozzles [107]. Small droplets are beneficial from the kinematical collision standpoint. A smaller droplet size (d_d) means a greater droplet concentration (C_{dn}) at the same water application rate and a higher particle capture efficiency (K_c) in Equation (3). Notably, at the same water application rate, C_{dn} is proportional to d_d^{-3}. Thus, despite a decrease in d_d, $d_d^2C_{dn}$ still increases. The velocity of droplets relative to particles (V_r) decreases with a reduced $\mathrm{d_d}$ if the droplet movement in the air is predominantly driven by gravity. However, high-pressure nozzles usually result in droplets with a relatively high initial velocity. According to Santangelo [108], for PM_1 (ultrafine particles with diameters <1 μm), a high-pressure system provides a large contact area, enhanced turbulence (for mixing), and an elevated V_r compared to a counterpart low-pressure system. All of these would increase particle collection efficiency. The half-life of 1 μm particles in a high-pressure spray chamber was found to be 50–100 times shorter than that in a low-pressure spray chamber, indicating better PM_1 removal by the former system [108].

Additional supporting yet indirect evidence has come from rain simulator experiments. Dr. Zhenming Zhang and colleagues at Beijing Forestry University utilized a rain simulator to generate artificial rain events with varying intensity levels. They subsequently investigated the deposition of air pollutants on selected plants, noting a substantial increase in PM deposition on plant leaves [109–111]. Although these studies again suggest the effectiveness of artificial rain in mitigating PM pollution, the experiments were different from real precipitation scavenging processes (in aspects such as droplet size and mixing height) but more similar to roadside sprinklers.

7. Summary and Perspective

Manipulating atmospheric processes enables the generation of artificial rain through cloud seeding, including glaciogenic seeding and hygroscopic seeding, implemented using aerial or ground-based rainmaking devices. The application of artificial rain has traditionally focused on drought relief and hail mitigation and been very cost effective. Recently, it has gained attention as a potential solution for regional air pollution control. The removal of air pollutants using rainfall is known as wet deposition or below-cloud precipitation scavenging. This process involves Brownian or kinematic collisions between PM and raindrops, as well as the absorption of gaseous pollutants into raindrops. Additionally, reduced PM concentrations during and after rainfall can be caused by source suppression, which mitigates the suspension and resuspension of fugitive dust. Aligned with these theories, multiple studies over the past two decades have observed decreased air pollutant concentrations during and after natural rain events. This reduction is notably impactful for water-soluble gaseous pollutants like SO_2 and NO_x, as well as coarse PM like PM_{10} and $PM_{2.5–10}$. However, for $PM_{2.5}$, a priority air pollutant in many developing countries, no consensus in the literature has yet been reached regarding its concentration change. A roadside sprinkler represents another example of the application of control theories. Multiple field studies have documented a significant reduction in PM concentrations upon spraying with fine water droplets.

In brief, previous research has generated a range of theories and evidence to endorse the use of artificial rain for air pollution control. However, this perspective is clouded by the absence of direct measurement data that confirm its efficacy in reducing air pollutants. This uncertainty is further compounded by three distinctions between artificial rain and natural rain scenarios.

- Rain characteristics. Artificial rain may differ from natural rain in terms of precipitation intensity, duration, raindrop size, and affected areas. These factors play a critical role in determining the effectiveness of air pollutant reduction. For example, the raindrop size in artificial rain can be influenced by various factors, including the choice of cloud seeding agents (e.g., those designed for warm cloud seeding versus supercooled cloud seeding) and the presence or intensity of updrafts within and below the clouds. Among all these characteristics, precipitation intensity (also referred to as rate) and duration are particularly crucial due to their significant impact on PM reduction efficiency (Table 2). Given that the majority of cloud seeding efforts have been directed towards drought relief (indicative of unfavorable meteorological conditions for heavy or prolonged rain formation), it is anticipated that the resulting artificial rain would be less intense and shorter in duration on average compared to natural rain. Indeed, drizzle or light rain were frequently observed after cloud seeding [112,113]. However, reports also indicate instances of moderate to heavy rains [114,115]. Heavy rains could occur during hail mitigation [116].
- Meteorological conditions. Artificial rain occurs as a result of weather manipulation. This indicates that the unaltered meteorological conditions would not naturally produce rainfall, or if they did, the rainfall would differ in terms of rate or duration. On the other hand, meteorological conditions have a large influence on the transport and transformation of air pollutants, including the formation of secondary air pollutants. For example, low stratus clouds are often correlated with temperature inversion that restricts the vertical dispersion of air pollutants; and they are occasionally targeted for cloud seeding [117]. Thus, artificial rain may not attain the same degree of air pollutant reduction as natural rain.
- Air pollution levels. A temporal misalignment between peak air pollution levels and favorable meteorological conditions for cloud seeding may limit effective air pollutant reduction. For example, convective clouds, a common target for cloud seeding, are often associated with air updrafts that might have dispersed air pollutants before rain formation. Additionally, cloud seeding could either hasten or delay the onset of rainfall, introducing further uncertainty regarding the efficiency of air pollutant reduction.

Despite advancements in the relevant sciences and technologies, cloud seeding remains a technology riddled with significant uncertainties, regarding its effectiveness, predictability, and controllability. The uncertainties also come from societal and regulatory domains, such as public perception and ecological concerns (e.g., deposition of hazardous pollutants to aquatic ecosystems) [118]. In developing countries that experience rapid urbanization and deteriorated air quality, cloud seeding may be further entangled with social and environmental equity. The cost of cloud seeding is substantial as it involves the delivery of chemicals to the cloud. Impoverished regions facing drought or severe air pollution may lack the financial resources to engage in cloud seeding initiatives, in contrast to wealthier areas. In summary, numerous technical and non-technical factors are involved in cloud-seeding-related decision making. The cost-effectiveness of artificial rain as a means of air pollution control should be evaluated comprehensively, considering technical, economic, and societal dimensions. As an initial step, it is imperative to conduct field assessments to quantitatively measure the efficiency of air pollutant reduction during and after artificial rain events.

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