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Atmospheric Ionization for Water Supply in Humid Regions of Iran: A Review Informed by the Saudi Experience

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Abstract

Water scarcity in arid and semi-arid regions such as Iran has intensified due to climate change, declining precipitation, and unsustainable water management practices. As conventional water harvesting methods become increasingly inadequate, innovative technologies for artificial rainfall enhancement are gaining global attention. Among these, atmospheric ionization has emerged as a promising non-chemical approach that releases charged particles into the lower atmosphere to stimulate cloud formation and precipitation. This review synthesizes the scientific principles, technological mechanisms, and regional feasibility of ionization-based cloud modification systems, with a particular focus on humid and topographically favorable regions of Iran. Areas such as the Caspian Sea coast, the Alborz and Zagros mountain ranges, and the Koohrang basin exhibit high relative humidity, persistent cloud cover, and strong orographic uplift—conditions that enhance the effectiveness of ion-induced precipitation. Drawing insights from Saudi Arabia's recent implementation of ionization towers under the National Center for Meteorology (NCM), the article compares climatic and geographical contexts to assess transferability. Despite Saudi Arabia's arid climate, preliminary results indicate measurable increases in rainfall, suggesting that ionization systems can be adapted to diverse environments when supported by real-time meteorological analysis and strategic deployment. The integration of autonomous Unmanned Aerial Vehicles (UAVs) and smart atmospheric monitoring platforms further enhances operational precision, enabling targeted ion release and optimized seeding windows. However, potential risks such as localized flooding, ecological disruption, and unintended cloud displacement must be carefully evaluated through environmental impact assessments and pilot studies. Overall, the review highlights the strategic potential of atmospheric ionization as a supplemental water resource strategy for Iran. By leveraging its favorable climatic zones and adopting hybrid technologies that combine ionization towers with UAV-based delivery systems, Iran could enhance seasonal precipitation and improve long-term water security. The findings underscore the need for interdisciplinary collaboration, policy development, and sustained monitoring to ensure safe and effective implementation.

Keywords: Ionization; Rain Enhancement; UAV, Iran; Humid Regions; Water Scarcity; Saudi Case Study

Introduction

Water scarcity has emerged as one of the most pressing global challenges, particularly in arid and semi-arid regions. The lack of safe drinking water has triggered socio-political instability and contributed to the formation of numerous crises worldwide [1]. As a vital resource for life and sustainable development, water underpins agriculture, industry, and public health [2]. However, climate change and anthropogenic pressures - especially from agricultural and industrial activities - have accelerated the depletion of freshwater resources [3].

Countries located in dry climatic zones face disproportionately severe water-related vulnerabilities, which can lead to significant socio-economic damage [4]. Iran, situated within the arid and semi-arid belt, is currently experiencing an acute water crisis. A combination of prolonged droughts, climate variability, and political-economic constraints has exacerbated the situation [1,5]. With an annual average rainfall of just 248 mm - far below the global average - Iran's semi-arid regions have increasingly transitioned into arid zones over the past four decades. By 2025, the country is projected to face a critical water shortage [6].

Conventional approaches to evaluating water scarcity are increasingly inadequate for addressing contemporary policy and resource management challenges, as they often overlook socio-cultural dimensions of water consumption [7,8]. Globally, scholars have emphasized the importance of equitable water allocation, institutional effectiveness, and community awareness in achieving water security [9-11]. Despite these efforts, persistent constraints in water availability and sustainability - coupled with growing inter-sectoral competition - continue to hinder human capital development [12-14].

In response to these challenges, technological interventions such as cloud seeding have gained attention as potential solutions for enhancing precipitation and managing water resources. Among these, atmospheric ionization - a non-chemical method that releases charged particles into the lower atmosphere to stimulate cloud formation - has emerged as a promising alternative. This review, in order to assess the feasibility and scientific basis of atmospheric ionization for rainfall enhancement, this section reviews the existing literature across four thematic areas. First, it outlines the historical development of cloud seeding technologies. Second, it introduces the principles and mechanisms of atmospheric ionization. Third, it explores the integration of ionization systems with smart platforms such as UAVs. Finally, it examines case studies and climatological data relevant to the application of this technology in Iran.

Historical Background of Cloud Seeding

The concept of cloud seeding as a method for enhancing precipitation has its roots in mid-20th century scientific experimentation. In 1946, American chemist Vincent Schaefer conducted the first successful artificial snowfall experiment at the General Electric Research Laboratory. By introducing dry ice into supercooled clouds, Schaefer demonstrated that ice crystals could be artificially generated, leading to snow formation [15].

Following this breakthrough, researchers explored other substances capable of initiating ice nucleation. Silver iodide (AgI), due to its crystalline similarity to ice, became the most widely used seeding agent. Numerous studies confirmed its effectiveness in cold cloud conditions [16,17]. Additional compounds such as dry ice [18], liquid carbon dioxide [19], and liquid nitrogen were also tested to lower cloud temperatures and stimulate precipitation.

Various methods for generating silver iodide particles were developed, including combustion-based techniques using acetone and other organic fuels [20,21]. While these chemical approaches proved useful in specific meteorological conditions, they also raised concerns regarding environmental toxicity, cost, and limited effectiveness in warm cloud environments.

In parallel, early studies began to investigate the role of atmospheric ions in cloud microphysics. Tzur et al. [22] suggested that ions could influence both warm and cold cloud dynamics, potentially enhancing droplet formation and precipitation. These findings laid the groundwork for alternative, non-chemical cloud modification techniques.

Over time, the limitations of conventional cloud seeding - such as dependency on specific cloud types, environmental risks, and operational costs - prompted the scientific community to explore more sustainable and adaptable technologies. This shift led to increased interest in atmospheric ionization, a method that modifies the electric field of the lower atmosphere to promote condensation and droplet coalescence without the use of chemical dispersants.

The historical evolution of cloud seeding reflects a broader transition from chemical-based interventions to environmentally conscious, data-driven approaches. Understanding this trajectory is essential for evaluating the potential of emerging technologies like ionization-based rainfall enhancement, particularly in water-stressed regions such as Iran.

Emergence of Atmospheric Ionization Technology

As limitations of conventional cloud seeding methods - such as environmental concerns, high operational costs, and reduced effectiveness in warm cloud conditions - became increasingly evident, researchers began exploring alternative technologies for artificial rainfall enhancement. Among these, atmospheric ionization has emerged as a promising non-chemical method that modifies cloud microphysics by releasing charged particles into the lower atmosphere.

The core principle of ionization-based cloud enhancement lies in altering the electric field near the Earth's surface to increase the likelihood of water vapor condensation and droplet coalescence. Ion generators, typically constructed from conductive materials like copper or aluminum, produce strong electric fields at their tips. These fields generate positive or negative ions that are transported upward by vertical air currents, increasing the charge density on suspended particles and promoting the formation of cloud droplets [23-25].

Scientific studies have shown that atmospheric ions can enhance the adhesion between water droplets and condensation nuclei, potentially reducing the time required for droplets to reach critical sizes for precipitation [26]. Additionally, the presence of electrical ions in visible atmospheric layers can increase the number of condensation nuclei, resulting in a more uniform distribution of water droplets and a stable vapor pressure gradient within clouds. This accelerates droplet aggregation and cloud formation.

Nicoll and Harrison [27] demonstrated that atmospheric ions - particularly under conditions of high humidity - can improve the stability of cloud layers and directly influence the initiation and intensity of precipitation events. These findings support the hypothesis that ionization-based systems are most effective in regions with favorable meteorological conditions, such as coastal zones and mountainous terrains with persistent humidity and thermal updrafts.

Recent technological advancements have enabled the integration of ionization systems with smart Unmanned Aerial Vehicles (UAVs), allowing for precise spatial targeting and real-

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time atmospheric monitoring. Compared to traditional manned aircraft, UAVs offer significant advantages in terms of cost-efficiency, safety, and operational flexibility [28,29]. Equipped with sensors for humidity, temperature, and pressure, drones can analyze atmospheric conditions on-the-fly and determine optimal windows for ion release.

Experimental programs in countries such as South Korea, Saudi Arabia, Australia, and the United States have demonstrated measurable increases in localized precipitation - ranging from 6% to 25% - when ionization systems were deployed under suitable conditions [30-32]. These results suggest that atmospheric ionization, when guided by meteorological data and implemented in appropriate regions, can serve as a viable supplement to traditional water resource strategies.

However, potential risks such as localized flooding, ecological disruption, and unintended cloud displacement must be critically evaluated before large-scale deployment [33-35]. As the technology continues to evolve, further research is needed to refine operational protocols, assess long-term impacts, and ensure environmental safety.

Integration with UAVs and Smart Systems

Recent advancements in atmospheric modification technologies have increasingly focused on integrating ionization systems with smart platforms, particularly Unmanned Aerial Vehicles (UAVs). This integration has revolutionized the operational flexibility, precision, and cost-effectiveness of artificial rainfall enhancement programs. Compared to conventional manned aircraft, UAVs offer significant advantages in terms of safety, maneuverability, and real-time responsiveness - especially in geographically complex or high-risk regions [28,29].

Equipped with advanced sensors - including humidity, temperature, pressure, and wind detectors - UAVs can continuously monitor atmospheric conditions and identify optimal windows for cloud seeding operations. These platforms are often enhanced by artificial intelligence (AI) algorithms that analyze meteorological data on-the-fly, enabling dynamic decision-making and targeted ion release (Miller et al., 2023).

Multirotor UAVs have proven particularly effective in executing microphysical experiments within cloud layers. The CLOUDLAB project, for instance, demonstrated that drones could perform precise measurements and dispersions at various altitudes, offering greater control than traditional piloted aircraft (Miller et al., 2023). This capability is crucial for ionization-based systems, which rely on accurate placement of charged particles in regions with high condensation potential.

Experimental programs across several countries - including South Korea, Saudi Arabia, Australia, and the United States - have validated the effectiveness of UAV-assisted cloud seeding. In South Korea, Jung et al. [28] conducted sensor-guided ionization experiments using UAVs, reporting up to a 25% increase in rainfall under favorable conditions. Similarly, Saudi Arabia's National Center for Meteorology (NCM) has deployed UAVs in conjunction with ionization towers, observing measurable improvements in precipitation in semi-arid zones [32,36].

In Wyoming, USA, and parts of Australia, UAVs have been used to disperse silver iodide and ionized materials, with preliminary results indicating a 6–11% increase in localized precipitation compared to control areas [30,31]. These findings underscore the potential of UAVs not only as delivery mechanisms but also as intelligent monitoring tools that enhance the precision and efficiency of weather modification efforts.

The integration of UAVs with ionization systems represents a paradigm shift in cloud seeding technology - moving from static, large-scale interventions to agile, data-driven operations. As Iran explores the feasibility of adopting ionization-based rainfall enhancement, leveraging UAV platforms could significantly improve implementation outcomes, particularly in mountainous and humid regions where terrain and weather variability pose operational challenges. Drones enable vertical take-off and landing operations in narrow areas, high-speed flight, and high-performance reconnaissance and surveillance. To expand the application of the unmanned aerial vehicle (UAV), it was developed to control a flare carrier mounted underneath it and conduct cloud seeding experiments. The flare carrier is designed to be capable of mounting four to six flares. Figure 1 shows the aircraft and instruments in the (a) UAV and (b) Korea Meteorological Administration (KMA)/National Institute of Meteorological Sciences (NIMS) Atmospheric Research Aircraft (NARA). Table 1 provides the respective specifications [28].

Table 1: Specification of UAV and NARA (Jung et al,2022).

	Unmanned aerial vehicle (UAV)	KMA/NIMS Atmospheric Research Aircraft (NARA)
Type	TR60	King Air 350 HW
Manufacturer	Korea Aerospace Research Institute (Korea)	Beechcraft (USA)
Size (m)	Wing: 3	L/W/H: 14.22/17.65/4.37
Maximum ceiling (km)	3	10
Maximum speed (km/h)	240	578
Maximum takeoff payload (kg)	200	7425

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Maximum flight time (hour)	5	5.5
Maximum range (km)	240	2872
Scientific instruments	Flare rack	Flare rack, CCNC, CIP, CDP, PIP, and WCM-2000

Figure 1: Aircraft and its instruments in (a) UAV and (b) NARA [28].

Case Studies and Applications in Iran

Iran's escalating water crisis, driven by climate change, prolonged droughts, and unsustainable resource management, has prompted researchers and policymakers to explore innovative solutions for enhancing precipitation. Among these, atmospheric ionization has gained attention as a non-chemical, environmentally friendly method with potential applicability in Iran's humid and mountainous regions [36] (Kamal, 2023).

Iran's unique topography and climatology offer favorable conditions for ionization-based weather modification. The Caspian Sea coast, along with the Alborz and Zagros mountain ranges, frequently exhibits high relative humidity, persistent cloud cover, and strong vertical air currents - key factors that support cloud formation and artificial rainfall enhancement [33,37,38].

The Alborz and Zagros regions are characterized by regular development of low- to mid-level clouds, orographic uplift, and relatively stable precipitation patterns. These features make them ideal candidates for deploying ionization towers or UAV-based ion dispersal systems [39]. Similarly, the Caspian coastal zone maintains high humidity throughout the year, with frequent thermal updrafts that facilitate the upward transport of charged particles, enhancing the likelihood of cloud condensation and rainfall [37].

One notable case study is the Koohrang region in Chaharmahal and Bakhtiari Province, where experimental ionization-based cloud seeding trials have been conducted. Results indicate that under suitable topographic and meteorological conditions, electric ionization can significantly increase the probability of precipitation [39]. Due to its climatic similarity to western Alborz and central Zagros, Koohrang serves as a valuable reference point for scaling up ionization technology across other mountainous regions in Iran.

Furthermore, moisture source analysis using Lagrangian dispersion models such as FLEXPART has shown that the Caspian Sea and its surrounding areas are primary contributors to atmospheric water vapor over northern Iran. These regions experience dominant autumn–winter precipitation, making them strategic targets for seasonal ionization interventions [40].

International case studies also offer valuable insights. Saudi Arabia's National Center for Meteorology (NCM), in collaboration with global experts, has launched a large-scale ionization-based rain enhancement project. Despite operating in arid conditions, preliminary reports indicate increased precipitation in targeted zones, validating the technology's potential under region-specific adaptations [32,36].

Taken together, these findings suggest that Iran's humid and topographically complex regions are well-suited for atmospheric ionization systems. By leveraging local climatological data, integrating UAV platforms, and learning from international experiences, Iran can develop a tailored framework for implementing ionization-based rainfall enhancement as part of its broader water security strategy.

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Materials and Methods

This review adopts a structured narrative synthesis approach to evaluate the scientific foundations, technological developments, and regional applicability of atmospheric ionization for artificial rainfall enhancement, with a particular focus on Iran's humid and mountainous regions.

Literature Search and Source Selection

To ensure a comprehensive and credible foundation for this review, a structured literature search was conducted across multiple academic databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. The search strategy combined both systematic and narrative approaches to capture foundational theories and emerging innovations in artificial rainfall enhancement.

Search terms included combinations of keywords such as: "cloud seeding," "atmospheric ionization," "artificial rainfall," "UAV weather modification," "precipitation enhancement in arid regions," and "non-chemical cloud seeding."

The inclusion criteria for source selection were as follows:

a) Publications dated between 2000 and 2024

b) Peer-reviewed journal articles or official institutional reports

c) Focus on non-chemical cloud seeding technologies, particularly ionization and electric field enhancement

d) Case studies or applications in semi-arid or humid regions, including Saudi Arabia, South Korea, Australia, the United States (Wyoming), and Iran

A total of 87 sources were selected, comprising 62 peer-reviewed articles, 18 technical reports, and 7 institutional documents. These sources were reviewed for relevance, methodological rigor, and applicability to the Iranian context. Priority was given to studies that provided empirical data, modeling insights, or operational evaluations of ionization-based cloud modification systems.

This selection process ensured that the literature review reflects both the historical evolution of cloud seeding and the latest advancements in ionization technology, with a particular emphasis on regional feasibility and climatological compatibility.

Thematic Categorization

To facilitate a structured and coherent analysis, the selected literature was organized into four thematic domains. This categorization enabled the synthesis of both theoretical foundations and practical applications of atmospheric ionization for artificial rainfall enhancement. Each domain reflects a critical aspect of the technology's development, implementation, and regional relevance:

a) Scientific Mechanisms of Atmospheric Ionization This category includes studies that explain the physical principles underlying ion-induced cloud formation, electric field manipulation, and droplet coalescence. It covers laboratory experiments, theoretical models, and field observations that demonstrate how charged particles influence cloud microphysics [23,25,27].

b) Technological Tools and Platforms This domain focuses on the engineering and deployment of ionization systems, including metallic ion towers, corona discharge units, and UAV-integrated platforms. It also includes sensor technologies and AI-based decision systems used for real-time atmospheric monitoring and targeted ion release [29] (Miller et al., 2023).

c) Global Case Studies and Pilot Projects This category encompasses empirical studies and operational reports from countries such as Saudi Arabia, South Korea, Australia, and the United States. These sources provide insights into implementation strategies, precipitation outcomes, and environmental considerations in diverse climatic settings [28,30,32].

d) Regional Assessments of Iran's Cloud Dynamics and Humidity Profiles This domain includes climatological and hydrological studies specific to Iran, focusing on regions with high relative humidity, frequent cloud formation, and favorable topography. It also incorporates modeling efforts using tools like FLEXPART to trace moisture sources and assess seasonal precipitation patterns [33,39,40].

This thematic framework provided a foundation for comparative analysis and contextual matching between global experiences and Iran's regional conditions, ensuring that the review remains both scientifically rigorous and locally relevant.

Comparative and Contextual Analysis

To assess the feasibility of atmospheric ionization for rainfall enhancement in Iran, a comparative analysis was conducted between international case studies - particularly Saudi Arabia's implementation - and Iran's regional climatic and topographic conditions. This approach enabled contextual matching based on meteorological parameters such as relative humidity, cloud formation patterns, and elevation profiles.

Saudi Arabia's ionization trials, led by the National Center for Meteorology (NCM), were primarily conducted in arid inland zones with low annual rainfall and limited cloud cover. Despite these constraints, targeted regions in the southwest - such as Asir and Jizan - exhibited favorable microclimates, including seasonal moisture inflows from the Red Sea and localized convective cloud development [32,36].

In contrast, Iran offers a more diverse and topographically complex environment. Regions such as the Caspian Sea coastal plains, the Alborz mountain range, and the western flanks of the Zagros Mountains consistently record high relative humidity levels

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(often exceeding 75%), frequent low- to mid-level stratocumulus cloud formations, and mean annual precipitation ranging from 700 to 1200 mm [37] (Roshani et al., 2013). These conditions are further enhanced by orographic uplift and persistent thermal convection, which support cloud development and increase the likelihood of successful artificial rainfall interventions.

The Koohrang region in Chaharmahal and Bakhtiari Province serves as a documented case study for ionization-based cloud seeding in Iran. Field trials conducted in this area demonstrated measurable increases in precipitation under controlled conditions, validating the potential of ionization technology in humid, mountainous terrains [39].

To support this comparative framework, meteorological modeling tools such as FLEXPART were used to trace moisture sources and assess seasonal cloud dynamics. These models confirmed that the Caspian Sea and its surrounding areas are primary contributors to atmospheric water vapor over northern Iran, particularly during autumn and winter months [40].

Overall, while Saudi Arabia's success in ionization-based rainfall enhancement under arid conditions is notable, Iran's climatological and topographic advantages suggest even greater potential for effective deployment. This contextual analysis highlights the importance of region-specific adaptation and supports the hypothesis that ionization systems can be optimized for Iran's humid and elevated zones.

Study Area Delimitation

To identify suitable regions within Iran for the application of atmospheric ionization technology, a multi-criteria assessment was conducted based on climatological, topographic, and hydrological parameters. The selection focused on areas with consistently high relative humidity, frequent cloud formation, and favorable terrain for vertical air movement - conditions that enhance the effectiveness of ion-based cloud modification systems.

Three primary zones were delineated as promising candidates for ionization-based rainfall enhancement:

a) Zone 1: Caspian Sea Coastal Plains This region exhibits year-round high relative humidity levels (typically above 75%), persistent cloud cover, and strong thermal convection. The proximity to the Caspian Sea ensures a steady influx of atmospheric moisture, making it one of the most favorable areas for artificial precipitation [37].

b) Zone 2: Alborz Mountain Range Located at altitudes ranging from 2,500 to 3,500 meters, the Alborz mountains experience regular low- and mid-level cloud formation due to orographic uplift. The combination of elevation, cloud dynamics, and seasonal precipitation patterns supports the deployment of ionization towers and UAV-assisted seeding systems (Roshani et al., 2013).

c) Zone 3: Central Zagros and Koohrang Region This zone includes the Koohrang area in Chaharmahal and Bakhtiari Province, where documented ionization trials have already been conducted. With mean annual precipitation between 700 and 1,200 mm and frequent stratiform cloud development, this region serves as a practical reference for scaling up ionization technology in similar mountainous terrains [39].

These zones were evaluated using data from meteorological modeling studies, hydrological assessments, and moisture source tracking via Lagrangian dispersion models such as FLEXPART. The results confirmed that northern and western Iran possess the necessary atmospheric and geographic conditions for successful implementation of ionization-based cloud enhancement [40].

By contrast, Saudi Arabia's ionization trials were conducted in arid inland regions with lower humidity and simpler physiographic features. This distinction highlights Iran's unique advantage in terms of natural cloud formation and moisture availability, reinforcing the strategic value of targeted regional deployment.

Regional Physiography and Climatic Conditions: Iran and Saudi Arabia

A comparative assessment of regional physiography and climatic conditions between Iran and Saudi Arabia was conducted to evaluate the contextual suitability of atmospheric ionization technology for artificial rainfall enhancement. Despite both countries being located within the semi-arid belt of the Middle East, they exhibit distinct topographic and meteorological profiles that influence cloud formation and precipitation potential (Figure 2).

Iran features a diverse and complex terrain, including coastal plains, high mountain ranges, and elevated plateaus. The Caspian Sea coastal region, the Alborz mountain chain, and the western flanks of the Zagros Mountains consistently record high relative humidity levels - often exceeding 75% - alongside frequent low- to mid-level stratocumulus cloud formations. These areas also benefit from orographic uplift and persistent thermal convection, which contribute to mean annual precipitation levels ranging from 700 to 1200 mm [37] (Roshani et al., 2013). Such conditions are highly conducive to ionization-based cloud modification, as they support stable cloud layers and enhance the likelihood of droplet coalescence.

In contrast, Saudi Arabia is predominantly characterized by arid desert plains and plateau regions with minimal annual rainfall - typically below 100 mm - and lower relative humidity. However, the southwestern parts of the country, particularly regions targeted by the National Center for Meteorology (NCM), exhibit localized microclimates favorable for cloud enhancement. These include seasonal moisture inflows from the Red Sea, convective cloud development, and appropriate altitudinal profiles for ion dispersion [32,36].

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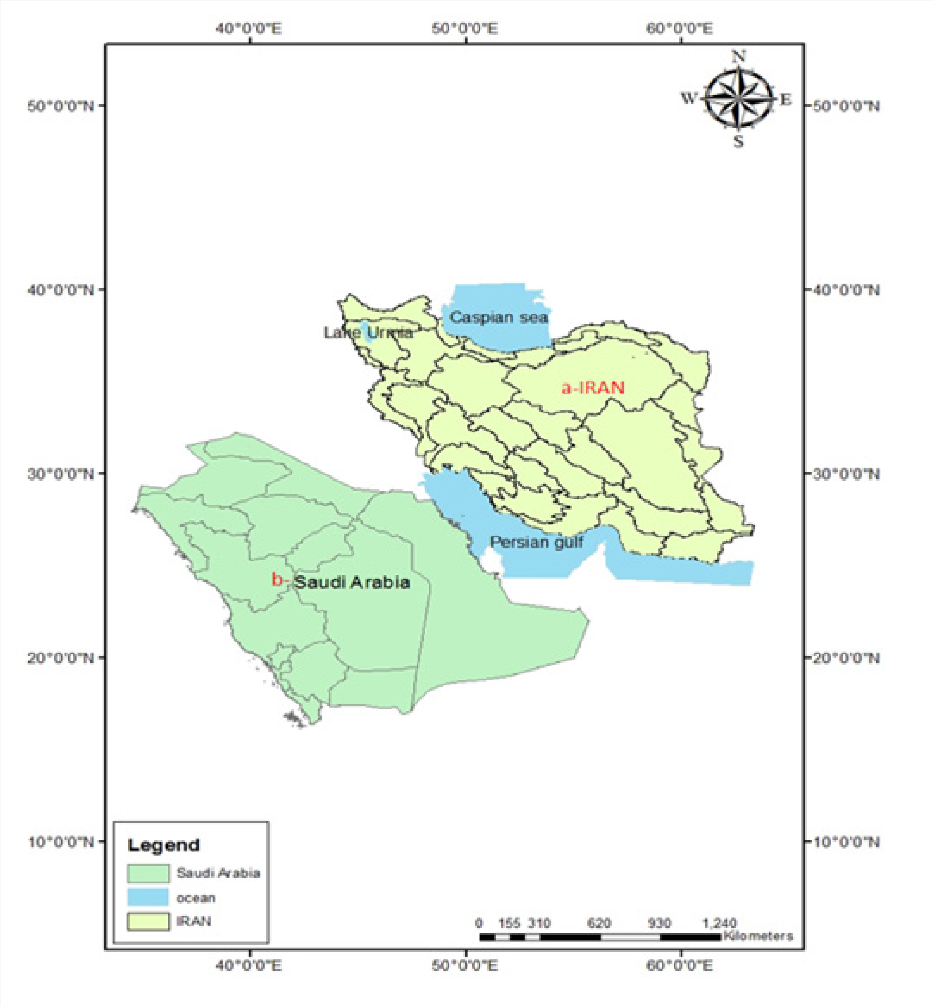

Figure 2: Study Regions in Iran and Saudi Arabia.

While Saudi Arabia's terrain is physiographically simpler, its successful implementation of ionization technology under controlled meteorological conditions demonstrates the adaptability of the method. Iran's more complex and humid landscape, however, offers a broader and potentially more effective platform for deploying ionization systems - especially when integrated with UAVs and real-time atmospheric monitoring.

This comparative analysis underscores the importance of tailoring ionization-based interventions to regional climatic and topographic characteristics. Iran's physiographic diversity and favorable cloud dynamics position it as a strong candidate for scalable and sustainable artificial rainfall enhancement using atmospheric ionization.

Discussion

The reviewed literature highlights a global shift toward environmentally sustainable and non-chemical methods for artificial rainfall enhancement. Among these, atmospheric ionization stands out due to its solid scientific foundation, operational flexibility, and compatibility with modern technologies such as UAVs and AI-based monitoring systems. This section synthesizes empirical findings, evaluates Iran's regional suitability, and outlines key operational and policy considerations for future implementation.

Effectiveness of Ionization Technologies

Field trials conducted in Saudi Arabia, South Korea, China, and the United States have demonstrated that ionization-based systems can lead to measurable increases in localized precipitation - typically ranging from 6% to 25% under favorable conditions [28,30,32,41]. These results validate the core hypothesis of this review: that charged ions, when released into humid and cloud-active layers, enhance droplet nucleation and coalescence, thereby accelerating rainfall processes.

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Notably, Saudi Arabia's success in deploying ionization systems in arid zones - despite limited humidity and cloud cover - underscores the adaptability of the technology when combined with real-time meteorological analysis and UAV-assisted targeting. Given Iran's more favorable climatic conditions, the potential for even greater hydrological impact is substantial.

Iran's Climatic and Topographic Advantage

Iran's northern and western regions - including the Caspian coast, Alborz, and Zagros mountains - offer a unique combination of high relative humidity, frequent stratiform cloud formation, and strong orographic uplift. These features naturally support vertical air movement and cloud stability, which are critical for effective ion transport and droplet activation [27,37].

Unlike Saudi Arabia's desert terrain, Iran's physiographic complexity enhances the interaction between atmospheric ions and suspended water particles. This suggests that ionization systems, if strategically deployed in these regions, could outperform similar interventions in more arid contexts.

Technological Integration and Operational Feasibility

The integration of UAVs, sensor networks, and AI-driven decision systems adds a transformative layer to ionization-based cloud modification. UAVs equipped with humidity, temperature, and pressure sensors can identify optimal seeding windows and deliver ions precisely into cloud-active zones [29] (Miller et al., 2023).

In China, a multi-site field trial using negative ionization systems demonstrated rainfall increases of up to 20%, supported by neural network modeling and historical weather comparisons [41]. These findings emphasize the importance of combining ionization hardware with intelligent software for adaptive and efficient deployment.

However, successful implementation in Iran would require:

a) Investment in infrastructure (ion towers, UAV fleets)

b) Technical training for operators and meteorologists

c) Real-time atmospheric data collection and modeling

d) Institutional coordination between the Iranian Meteorological Organization, Ministry of Energy, and academic research centers

Design and Deployment of Ionization Systems: Lessons from China

China's deployment of four ground-based ionization systems - one in Wushaoling and three in Liupan Mountain - offers valuable insights into site selection and system design. These units were installed at elevations between 2,771 and 3,529 meters, on windward slopes, and aligned with dominant wind directions to maximize ion dispersion [41].

Such strategic placement, guided by topographic and meteorological modeling, can inform similar deployments in Iran's mountainous zones. The use of elevation, slope orientation, and cloud proximity as design criteria ensures optimal ion transport and interaction with cloud layers. As shown in Figure 3 and summarized in Table 2, the systems were installed at high elevations on windward slopes to maximize ion dispersion. Their placement was strategically guided by dominant wind directions and proximity to cloud-prone altitudes [41].

Table 2: Technical and Operational Details of Ground-Based Negative Ionization Systems in China., Adapted from Zheng et al. (2021).

Data Range	Operation Period	Install Date	Elevation (m)	Longitude €	Latitude (N)	System ID
May 2019–Nov 2020	Jul–Nov 2020	Nov-19	3529	102°53′29″	37°12′03″	W1
Apr–Nov 2020	Aug–Nov 2020	Apr-20	2790	106°11′41″	35°39′42″	L1
Apr–Nov 2020	Aug–Nov 2020	Apr-20	2771	106°12′17″	35°39′41″	L2
Apr–Nov 2020	Aug–Nov 2020	Apr-20	2837	106°12′06″	35°39′47″	L3

Environmental and Policy Considerations

While atmospheric ionization is generally considered safer than chemical cloud seeding, potential risks must be addressed. These include:

a) Localized flooding due to enhanced precipitation

b) Ecosystem shifts from altered rainfall patterns

c) Unintended cloud displacement affecting neighboring regions

To mitigate these risks, pilot programs should be accompanied by environmental impact assessments, adaptive regulatory frameworks, and transparent public communication [33,34]. Lessons from Saudi Arabia emphasize the importance of regional customization, continuous monitoring, and inter-agency collaboration [42-58].

Limitations and Future Research Directions

Despite promising results, the current body of research in Iran remains limited in scope and duration. Most domestic studies - such as the Koohrang trial - are short-term and lack longitudinal data [39]. To advance the field, future research should focus on:

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a) High-resolution regional climate modeling

b) Long-term hydrological impact assessments

c) Integration with national water resource planning frameworks

d) Development of a unified protocol for weather modification programs

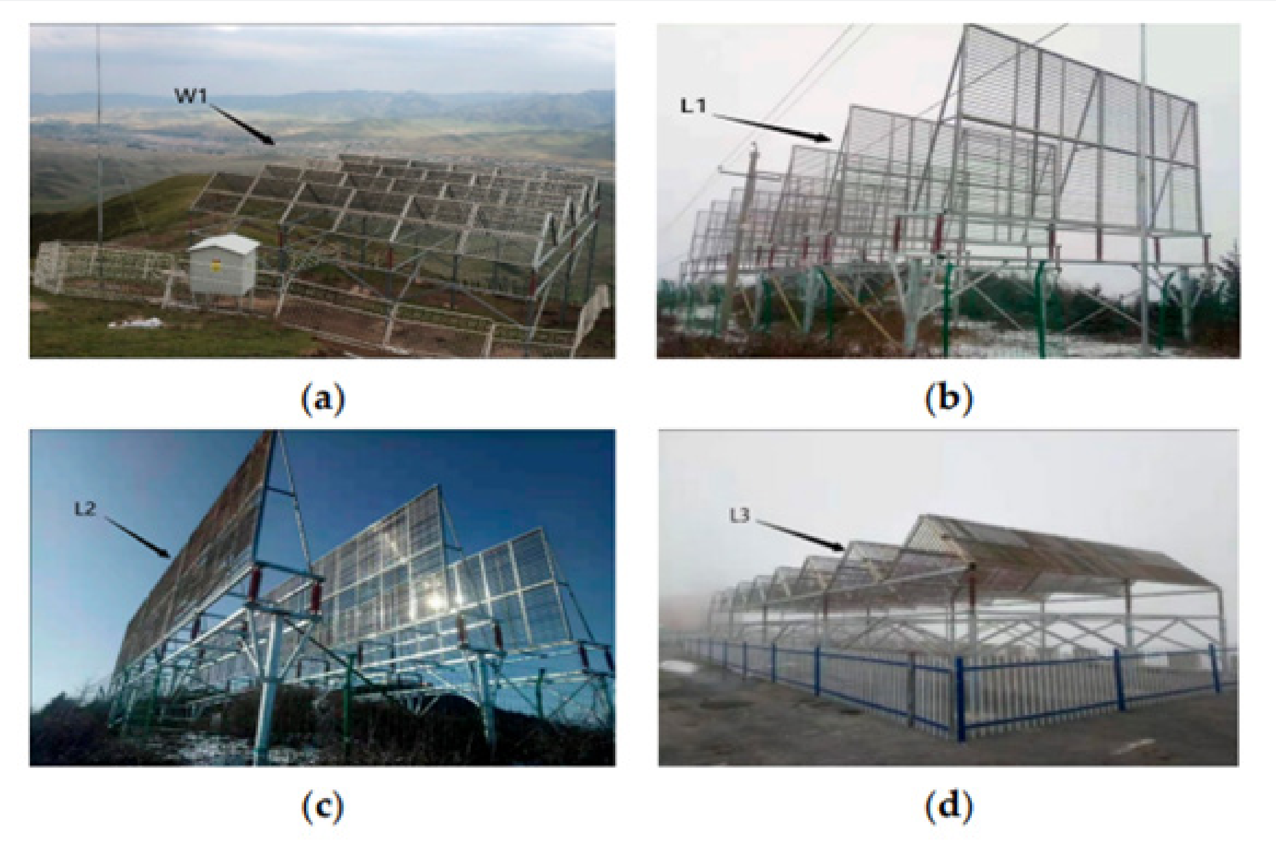

Figure 3: (a) The ground-based negative ionization system in Wushaoling (W1); (b) The first ground based negative ionization system in Liupan Mountain (L1); (c) The second ground-based negative ionization system in Liupan Mountain (L2); (d) The third ground-based negative ionization system in Liupan Mountain (L3). Table 1 presents more detailed information on one ground-based negative ionization system at Wushaoling and three at Liupan Mountain. Adapted from Zheng et al. [41].

Conclusion

This review has explored the scientific foundations, technological advancements, and regional feasibility of atmospheric ionization as a non-chemical method for artificial rainfall enhancement. Drawing upon global case studies and climatological assessments, the findings suggest that ionization-based systems - particularly when integrated with UAVs and smart monitoring platforms - offer a viable and environmentally sustainable alternative to conventional cloud seeding.

Iran's unique climatic and topographic conditions, especially in the Caspian coastal plains, Alborz mountains, and Zagros region, present a strategic opportunity for deploying ionization technologies. High relative humidity, frequent cloud formation, and strong orographic uplift in these zones create an ideal environment for ion-induced cloud activation and precipitation.

International experiences, such as those in Saudi Arabia, South Korea, and China, demonstrate that with proper design, real-time meteorological analysis, and adaptive deployment strategies, ionization systems can achieve measurable increases in rainfall. These insights are particularly relevant for Iran, where water scarcity poses a critical challenge to sustainable development.

However, successful implementation requires more than technical feasibility. It demands coordinated efforts across governmental agencies, investment in infrastructure and training, and the establishment of regulatory frameworks to ensure environmental safety and public trust. Pilot programs, long-term

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impact studies, and integration with national water resource planning are essential next steps.

In conclusion, atmospheric ionization represents a promising frontier in weather modification science. For Iran, it offers not only a potential solution to water scarcity but also a platform for innovation, collaboration, and resilience in the face of climate uncertainty. With strategic planning and interdisciplinary engagement, ionization-based rainfall enhancement could become a cornerstone of Iran's future water management strategy.

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