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Review Article

Atmospheric Fungal Spore Injection: A Promising Breakthrough for Challenging the Impacts of Climate Change Through Cloud Seeding and Weather Modification

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Abstract

Cloud seeding is a technique used to enhance precipitation in drought-prone areas, support agricultural productivity, ensure water supply for human consumption, improve hydropower generation from dams, lessen hurricanes, cool urban heat, and disperse fog in airports. Growing global population size and climate change are the biggest impetus for weather modification and cloud seeding operations. Currently, salt powders like silver iodide, potassium iodide, sodium chloride, calcium chloride, dry ice (solid carbon dioxide), and liquid propane are widely used as ice nucleating particles for cloud seeding purposes while in natural cloud formation, and precipitation particles from dust storms, mineral dust and biological aerosols (like spores, pollen, bacteria) are the dominant ice nucleators. Having this knowledge on hand and the ubiquitous nature of fungi on the other hand; it is feasible to exploit the ice nucleating ability of fungal spores and use it as potential candidates for cloud seeding and weather modification operations.

Introduction

Climate change is been posing widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere. It is unequivocal that anthropogenic activity is the major driver for climate change thereby affecting every region across the globe leading to widespread adverse impacts, related losses, and damages on the natural environment and human communities [1]. Bigger and louder alarms for extremes such as heatwaves, heavy precipitation, droughts, forest fires, and tropical cyclones are been observed for a couple of decades influencing human life and biodiversity [2,3]. Rapid urbanization and industrialization coupled with the fast growth of global population size leads to over-exploitation of the natural environment through deforestation, mining, and irresponsible land use which cause severe ecosystem destruction [4]. Parallel to environmental exploitation huge amounts of pollutants are emitted into the atmosphere and dumped into the land and aquatic environment thereby posing significant pollution in all ecosystems (terrestrial, aquatic, and atmospheric) [5]. With rough approximation 3.3 to 3.6 billion people reside in environments that are extremely vulnerable to climate change where millions of people are exposed to acute food insecurity (720 - 811 million people worldwide faced hunger in 2020) and reduced drinking water security [6]. A rise in the average global surface temperature of 1.09 °C between 1850 and 2020, and 0.95-1.2 °C in the most recent ten years, is indicative of climate change. The effects of climate change on agricultural harvest due to constant fluctuations in rainfall (amount, intensity, frequency, and type (e.g. snow vs. rain)) and shifts in the rainy season [7] and due to ocean warming and ocean acidification which adversely affects food production from fisheries and aquacultures in oceanic regions; hindering the efforts to meet Sustainable Development Goals (SDG1 and SDG2). Global warming can cause higher evaporation from water bodies, soil, and vegetation ("Atmospheric thirst") enhancing atmospheric water vapor levels and exposing surface ecosystems to drought. Higher atmospheric water vapor causes intense precipitation events even in regions with low rainfall levels “*It never rains but pours*” posing flooding risks [8]. In contrast to rapid, strong rainfall that causes soil runoff and flooding and leaves the soil dry after hours, moderate rainfall that falls and percolates into soil particles is preferred in agricultural areas for a longer period which is convenient for efficient crop growth and good harvest [9]. Condensation of atmospheric water vapor leads to the formation of clouds which fall back as precipitation to the earth’s surface. Furthermore, clouds control the planet's average temperature, help cool the planet by reflecting solar energy or shortwave radiation into space [10], and help warm the planet by acting as a blanket to trap thermal energy or longwave radiation emitted from the surface of the Earth and lower atmosphere [11]. Cloud systems additionally aid in uniformly dispersing solar radiation across the surface of the Earth [12]. Clouds are formed with water droplets and tiny particles like mineral dust and hygroscopic biological particles or bioaerosols which function as the core or nucleus of cloud condensation nuclei or ice nuclei [13]. This understanding and the growing water demand drove pioneering researchers in the 1950s to engage in an intensive scientific quest and trial to solve the scarcity of rainfall in some regions which finally led to a promising rain-inducing technique called cloud seeding in the last six decades that enabled to regularly harness the cloud’s moisture and pull it to Earth, bringing water to parched communities and landscapes around the world. The process involves “seeding” existing clouds with a harmless substance called silver-iodide to give water droplets a particle to converge around, allowing them to form an ice crystal [14]. As per the scientific trials done to enhance precipitation from wintertime orographic cloud systems (cloud systems over mountain ranges) through a static cloud seeding method, it was found that a cloud’s natural precipitation efficiency can be enhanced by converting supercooled water to ice upstream and over a mountain range in such a manner that newly created ice particles can grow and fall to the ground as additional snow on a specified target area [15]. Following cloud-seeding activities, researchers investigated the efficiency of silver iodide as INP by sampling the levels of silver iodide in a mountain snowpack and confirmed that it incorporated into ice crystals and deposited as snow, ratifying that seeding orographic clouds containing supercooled water with silver iodide can efficiently produce plumes of ice particles that originate downwind of the seeding location and reach the ground through precipitation growth and fallout [16]. Furthermore, Silver iodide (AgI) can be also dispersed as airborne pyrotechnically from an aircraft within clouds having lower cloud top temperatures (colder than -6 to -8 °c). Before applying AgI cloud seeding, physical records such as those that show which orographic clouds are suitable for AgI treatment, when and where Supercooled Liquid Water (SLW) is present in clouds, and the circumstances under which plumes of AgI released from the ground or the air reach clouds upstream and within target river basins should be determined. Natural cloud formation and precipitation occur with the dominant ice nucleating particles like dust (eg: Dust from sand storms in Asia, Africa, and the Middle East), pollen, and spores which act as the nucleus of the ice crystal, in contrast to the artificial cloud seeding process that uses small silver iodide particles [17]. When the tiny water droplets hanging in clouds as precursors clump together forming larger drops or freeze together to form larger crystals, they start to fall as precipitate. Droplets commonly freeze at warmer temperatures via heterogeneous nucleation triggered by Ice Freezing Nuclei (IFN), either internal to the droplets or through collisions with aerosol. To achieve this knowledge scientists engaged in understanding the interaction between the natural atmospheric INP, water droplets, and ice crystals. A single drop of precipitation requires more than one million small droplets to converge. Polluted regions do not get sufficient rainfall which indicates that not all atmospheric aerosols have the same impact on clouds. This review aims to address the possibility of using fungal spores as alternative ice nucleating agents for cloud seeding and weather modification.

Discussion

Fungal spores as INP for cloud seeding

As the human population is on the cusp of a water crisis there it is posing pressure on freshwater resources. Moreover, climate change and population growth have increased the demand for water in arid regions [18,19]. In recent decades a new geoengineering strategy is been found to enable rain and enhance the amount of precipitation using cloud seeding through atmospheric injection of ice nucleating particles (INP) [20]. *Fungal spores* are found to account for up to 45% of coarse particle mass (>1 µm). The natural abundance of fungal spores in terms of class level taxonomic ranking is different in different studies depending on the sampling approach (wet deposition, dry deposition, air pumping), the efficiency of sample collecting instruments, amount of investigated samples, study region, and climate zones [21]. For instance *Dothideomycetes, Tremellomycetes, and Microbotryomycetes* are found to be the three most abundant classes in most studies which used the dry deposition approach [22] while based on air sampling strategy *Cladosporium (Dothideomycetes), Ustilago* (Ustilaginomycetes)*, Alternaria (Dothideomycetes) and mushroom* (Agaricomycetes) *spores are abundant [23].* Spores of many fungal classes such as Dothideomycetes, Agaricomycetes, Eurotiomycetes, Ustilaginomycetes, and so on have already been confirmed to be among the prominent biological ice nucleating particles in the upper atmosphere [24] (Table 1). So higher emission of fungal spores along other biological INP (like bacteria and pollen) and inorganic INP (like mineral dust) can potentially affect the hydrological cycle and precipitation [25]. The small protein subunits (50 amino

Table 1: Fungal spores with IN ability.

Investigated Classes	Investigated Genus/species	findings	References
Urdinomycetes	*Puccinia aristidae, P. lagenophorae, P. allii, P. striiformis, P., graminis f. sp. Tritici, Hemileia vastratrix, P. triticina, P. graminis f. sp. tritici*	Urediospores are active ice nucleators at > -10 °C and harbor ice nucleation active bacteria.	[40]
Agaricomycetes	*Geastrum saccatum, Lycoperdon pyriforme, Russula aeruginea, Russula pulchra, Russula variata, Suillus brevipus, Lactarius hygrophoroides, Agaricus bisporus, Amanita muscaria, Boletus zelleri, Lepista nuda, Trichaptum abietinum*	Basidiospores are especially effective as nuclei for the formation of large water drops in clouds. Spores of agaricomycetes are among the naturally abundant airborne spores following *Cladosporium spp*.	[41]
Ustilaginomycetes	*Ustilago nuda, Ustilago nigram , Ustilago avenae*	On average, *Ustilaginomycetes* spores displayed higher nucleating ability compared to *Agaricomycetes* and *Eurotiomycetes*.	[42]
Eurotiomycetes	*Aspergillus brasiliensis, Aspergillus niger, Penicillium sp., Penicillium brevicompactum*	Spores of Eurotiomycetes displayed lower IN activity compared to *Ustilaginomycetes* and Agaricomycetes.	[42]
Dothideomycetes	*Cladosporium sp.*	Spores of **Cladosporium** may compete with other active INs such as mineral dust at temperatures from -25 °C to -35 °C, even though surface hydrophobins tend to reduce their IN activity. Spores of *Cladosporum spp*. are most abundant in atmospheric ecosystems.	[43]
Mortierellomycetes	*Mortierella alpina*	The IN produced by M. alpina seems to be small extracellular proteins of 100 – 300 kDa which are not anchored in the fungal cell wall.	[44]
Sordariomycetes	*Fusarium acuminatum,* *Fusarium avenaceum*	Ice nucleation activity of evaluated species was stable at pH levels from 1 to 13 and tolerated temperature treatments up to 60 °C.	[25]

acids) found on the surface of spores are responsible for the IN nature of fungal spores. Geoengineering researchers can exploit this capability of spores as IN agents for cloud seeding and other climate modification efforts as an alternative to salt powders like silver iodide to deliberately alter atmospheric processes and mitigate the effects of climate change. Being hydrophilic; fungal spores can act as Cloud Condensation Nuclei (CCN) where tiny particles around which water vapor condenses to form cloud droplets [26]. Thus, dispersing fungal spores into the atmosphere may raise the concentration of CCN, enhancing cloud formation. Spores can be launched using an aircraft or using the static approach in cold regions where clouds consist of supercooled water droplets to enhance the formation of ice crystals, triggering precipitation (e.g., snow or rain) to solve water scarcity or managing drought conditions [27]. In addition, enhancement of precipitation through fungal spore cloud injection can boost hydropower generation from big dams and agricultural harvest from rainfed crops and advanced irrigation systems that depend on dams or lakes (Figure 1). Moreover fungal injection could be used to enhance cloud albedo, or the reflectivity of clouds; aiding on radiation management. The quantity of solar radiation that reaches the Earth's surface may be decreased by increasing cloud cover and thickness, which would reflect the short-wave radiation into space [28]. The cooling effect is one goal of solar radiation management through geoengineering strategies. The earth might get cool by around 1.4 K through seeding mid and high-latitude cirrus cloud seeding, which possibly can also reduce rainfall slightly [29]. Since cooling is greatest at high latitudes, it might help to keep the Arctic sea ice from melting [30]. Furthermore; Clouds regulate Earth's average temperature by operating as a blanket to retain or downward flux thermal energy or longwave radiation emitted from the Earth's surface and lower atmosphere. However, the impact of clouds on the atmospheric energy balance is not as clear-cut [31]. High clouds warm the atmosphere by reducing the upward emission of longwave radiation, low clouds can cool the atmosphere by increasing the downward emission of longwave radiation [12].The radiative interactions of clouds result from the scattering, absorption, and emission of photons by cloud particles. The net effect of clouds is to cool Earth by 18 W m−2 in the global mean [28]. Fungal spores could also potentially be used in marine cloud brightening efforts; where low-level clouds are common to enhance cloud reflectivity over oceans [32]. Some fungi release Volatile Organic Compounds (VOCs) that can lead to the formation of Secondary Organic Aerosols (SOA) which can contribute to atmospheric cooling through scattering sunlight or by acting as additional CCN in cloud formation. So deliberate dispersing of these fungi can promote SOA formation thereby enhancing cloud formation and atmospheric cooling [33]. SOA could also mitigate the warming effects of greenhouse gases by increasing cloud cover or reflectivity. Being natural makes spores more biocompatible than using artificial chemicals or other synthetic cloud-seeding agents. Fungal spores are biodegradable organic particles reducing the effect of using non-biodegradable chemical INPs. In addition; the ubiquitous habit of fungi can help to produce fungal spores on a large scale easily and cost-effectively. Moreover, fungal spores upon deposition germinate and contribute to the decomposition of wastes improving soil fertility and environmental sanitation as brooms of nature [34,35]. Germination of ascospores and basidiospores of specific fungal genera form a mutualistic association with green algae (eg: Lichen) [36] and green plants (eg: Mycorrhizae) enhancing mineral and water absorption to their partner through their vast mycelial network; boosting plant growth and photosynthetic productivity by photobiont partners. Furthermore, fungi improve plant tolerance and fitness to biotic and abiotic stresses [37]. Environmental scientists use the lichen community as an indicator of

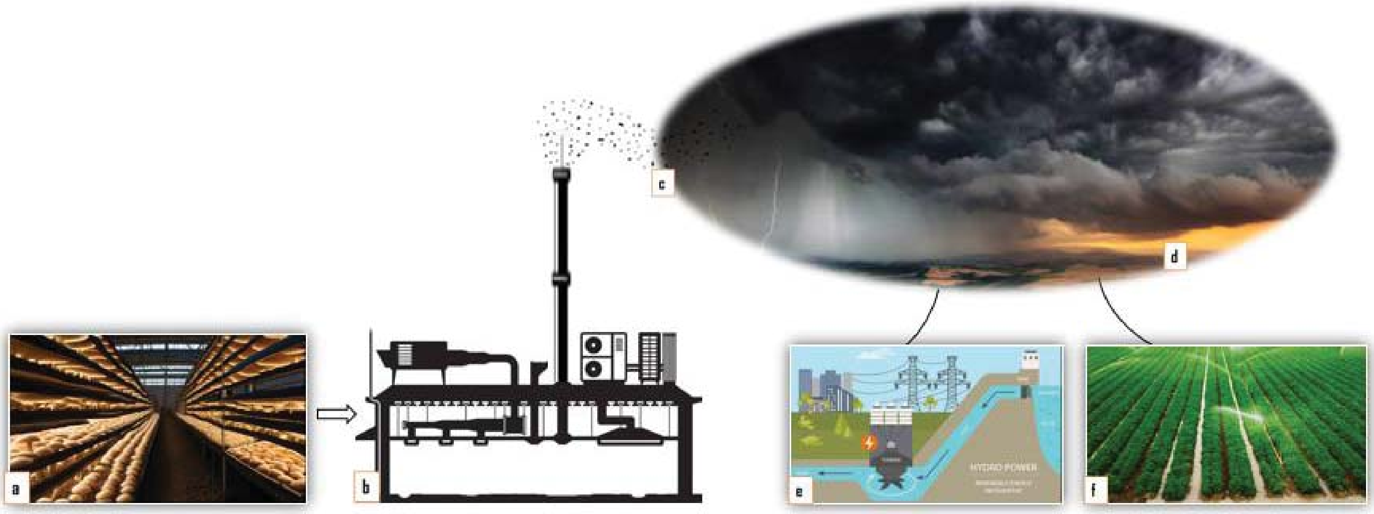

Figure 1: Hypothetical ground-based fungal spore launching for cloud seeding purpose: macro-scale indoor fungal cultivation (a), cultivation room equipped with an air blower, air sucking, and generating machines (b), spore dispersal through a plumbing vent (c), fungal spores induces and enhances precipitation (d), dams collect sufficient water thereby maximizing hydropower generation (e) and agricultural productivity (f). (Source: https://mushroom-growing.com/indoor-mushroom-farm/ (a), https://www.istockphoto.com/de/vektor/zentrale-klimaanlage-für-gebäude-gm113015 560 4-298811431 (b), https://www.istockphoto.com/de/fotos/heavy-rain-in-the-mountains (d), , (e) https://home.howstuffworks. com/ irrigation.htm (f))

environmental pollution since they are sensitive to heavy metal and nitrogen pollution [38,39]. Considering these advantages of using fungal spores as INP for cloud seeding and weather modification operations can contribute to maintaining environmental sustainability rather than using salt powders and other chemicals for these operations. Fungal spore injections could be designed to influence specific ecosystems or climate zones where fungal species are already part of the natural bioaerosol load, potentially reducing the ecological impact of cloud seeding.

Cloud seeding approaches

Three new cloud-seeding strategies have been designed as a result of ongoing research on weather modification for more than 50 years: the dynamical cloud-seeding hypothesis, the hygroscopic cloud-seeding hypothesis, and the static cloud-seeding hypothesis [45]. Dynamical cloud-seeding is a complex sequential attempt where air currents are vertically lifted invigorating water or moisture through the clouds thereby releasing a sudden latent heat of fusion and increasing the buoyancy of the cloud which generates a more vigorous cloud and rain [46]. This approach is more complex and requires larger volumes of seeding material. The hygroscopic cloud (warm cloud) seeding technique is seeding warm-based cumulus clouds with giant hygroscopic nuclei (salts powders through flares or explosives) into the lower part of clouds [47] to enhance the droplet coalescence on the seeded giant cloud condensation nuclei, thereby increasing The precipitation efficiency in the updraft of the cumulus cloud. Hygroscopic particles are either dropped or launched from planes [48]. Static (cold cloud) or glaciogenic seeding spreads ice-nucleating particles (silver iodide or dry ice (solid carbon dioxide)) into clouds already containing moisture (temperature below 0 °C) that condenses around the nuclei and falls as precipitation. Under the correct circumstances, static cloud seeding will cause water to begin to freeze, producing latent heat that has the potential to drive the cloud upward producing a more powerful cloud and rain by making the cloud larger and more resilient. Snow can start to fall within fifteen to thirty minutes of launching silver iodide into the skies. Dry ice and liquid nitrogen can also be utilized as rain-enhancing catalysts [49].

Approaches for atmospheric delivery of INPs

Various techniques have been proposed for delivering the INP. Cloud seeding is usually accomplished via aircraft delivery or different kinds of ground-based generations (Figure 2). While aircraft deployment is more effective (~10% - 20% additional yield) than ground-based generation (~10% additional yield), it is also more expensive [50]. Drones could be used to bridge the gap between the cost-benefit of ground-based systems and the effective reach of airborne systems. Generators or canisters launched from anti-aircraft guns or rockets are also used for injecting INP [51]. Modified artillery shells might have the necessary capability, but require a polluting and expensive propellant charge to loft the payload. So non-polluting artillery could be designed as an alternative [52]. An Automated High-Output Ground Seeding System (AHOGS) or simple ground-based INP generators are also widely used static INP launching mechanisms. AHOGS takes advantage of desirable wind and weather patterns to get their seeding agents up into the clouds without the need

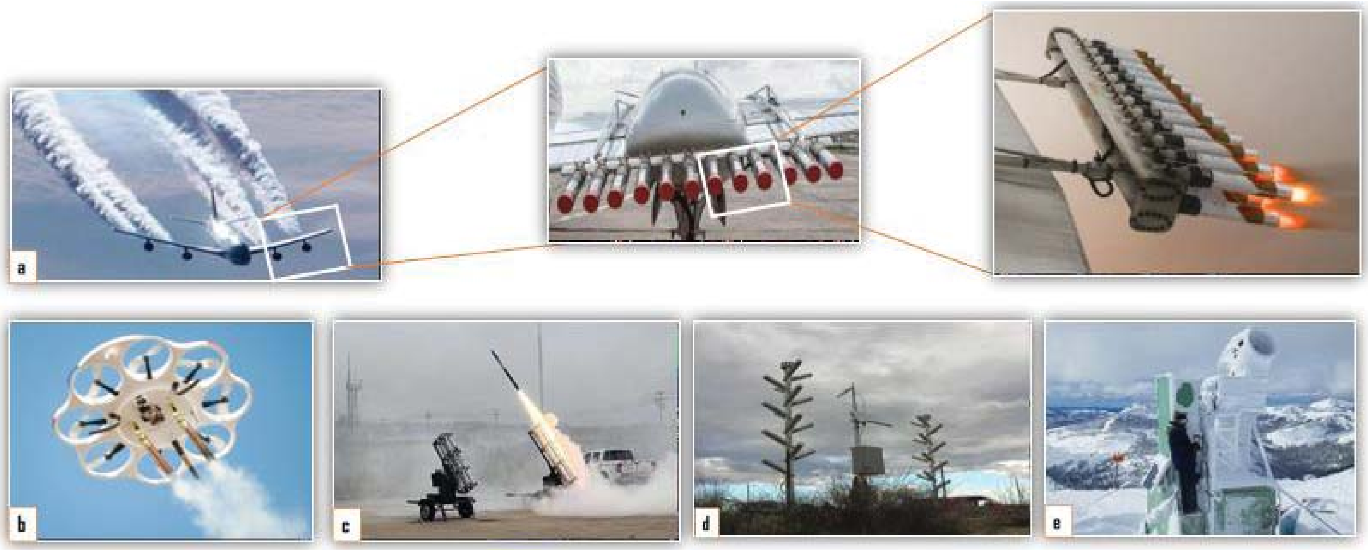

Figure 2: Mechanisms of launching INPs; aircraft deployment (a), drone-based dispersal (b), rocket-based INPs injection (d), automated high-output ground seeding system (AHOGS) (d), ground-based cloud-seeding generator (e). (Sources: https://www.bibalex.org/SCIplanet/en/Article/Details.aspx?id=128, (a), (b), https://x.com/wulei2020/status/1530456011244380160 (c),https://www.scientificamerican.com/ article/drought -ridden-l-a-tries-rainmakers-to-tap-storm-clouds/ (d),) (e))

for a flight. High-altitude balloons can be used to lift precursor gases, in tanks, bladders, or in the balloons' envelope. Xue L, et al. [53] stated that airborne seeding from lower flight paths increased precipitation on the windward side of the mountain, whereas ground-based seeding increased precipitation on the lee side of the mountain.

Because fungal species are equipped with massive enzyme kits which is attributed to the decomposition and growth on a wide substrates through degradation of all organic carbon polymers within substrates [54] it is easier to cultivate target fungal species in a closed indoor environment through solid culture technique to generate massive spores during a target season for cloud seeding purpose. The cultivation halls should be designed with air blowers for indoor spore dispersal when fungal cultures are matured and an air suction system to suck indoor air containing spores and launch fungal spores alongside it through a long plumber vent on the roof of the cultivation house into the air. The plumber vent should be long enough to encourage vertical spore delivery into the lower clouds and to avoid lower dispersal of spores which can cause faster deposition (Figure 1). Moreover, fungal cultivation and spore generation rooms should be built far away from residential sites.

Potential upshots of cloud seeding with fungal spores and considerations

Environmental and Health Risks: even though silver iodide is considered relatively low in toxicity, its accumulation in the environment can affect water quality, soil microbial diversity, soil content, and wildlife. Similarly, injecting large quantities of fungal spores into the atmosphere could pose health risks, particularly for individuals with allergies, asthma, or compromised immune systems because most fungal species are opportunistic. So dispersing spores at lower atmospheric levels may result in reducing air quality at the boundary layer; compromising the respiratory well-being of humans and animals [55]. High concentrations of fungal spores could exacerbate respiratory problems, and long-term exposure risks would need to be thoroughly evaluated [56]. Introducing fungal spores into environments where they are not naturally abundant could have unintended consequences for ecosystems. The consequences of stratospheric aerosol injection on ecological systems are unknown and potentially vary by ecosystem with differing impacts on marine versus terrestrial biomes. Fungal bioaerosols might influence not only cloud dynamics but also the balance of microbial ecosystems in the atmosphere and terrestrial ecosystem, potentially affecting soil microbiota, agriculture, natural flora, and water quality through spore deposition. Some spores can be phytopathogenic to specific flora (Figure 3). Moreover; like any geoengineering strategy, fungal injection would need to navigate ethical concerns about manipulating natural systems, particularly on a global scale. There could be unintended geopolitical consequences if one region benefits from cloud seeding while another suffers adverse effects (e.g., disruption of natural precipitation patterns) [57]. Aerosols can also absorb some radiation from the Sun, the Earth, and the surrounding atmosphere which can cause changes in the surrounding air temperature and could potentially impact the stratospheric circulation, which in turn may impact the surface circulation [58]. Furthermore; altering precipitation patterns in one area could inadvertently affect weather systems in another, leading to unforeseen changes in local

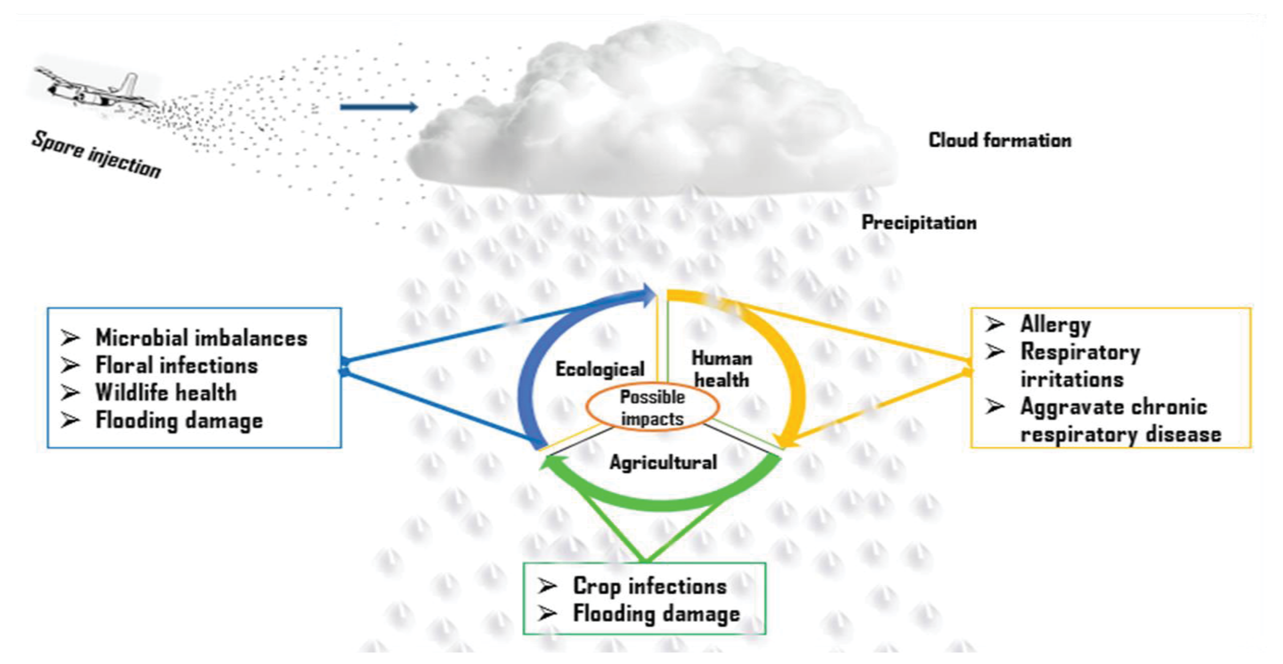

Figure 3: Possible impacts of using fungal spores as ice nucleating agents for cloud seeding and weather modification operations.

climates. So to track any effects on the environment or human health, controlled field studies of fungal cloud seeding would be required. Additionally, because of the trauma of endemics and pandemics the world endured in the last decades, people's awareness of the positive side of bacteria is lower globally than their awareness of the dangerous effects of aerosolized microbes. Moreover, some traditional human societies may see these operations as intervening with nature which can cause severe divine responses such as floods, droughts, and famine to human actions or moral transgressions. So many societies may psychologically not accept modifying weather and precipitation levels through fungal spore dispersal. So the role of religious leaders along with political leaders is important in convincing such societies. In terms of research study fungi are less scrutinized domain compared to other microbes; so deeper studies are required to ensure the spore impacts and interaction upon deposition to persuade farming societies.

Applications and Limitations of cloud seeding

The majority of research on deep-convective cloud-seeding scenarios assessed orographic cloud seeding through modeling, and they verified that the impacts of seeding on augmenting precipitation were optimistic regarding rainfall distribution and quantity. It is now evident from physical data that orographic clouds containing supercooled water that have been seeded with AgI form plumes of ice particles that arise downwind from the seeding spot and fall out and grow onto the ground as precipitation [59]. AgI plume dispersion and the growth and fallout of precipitation produced by AgI aerosol have been simulated using models in many previous studies. The efficiency of cloud seeding majorly depends on various meteorological (cloud moisture, cloud-top temperature, and wind speed) and topographical conditions [60]. However, it is unclear how these interact with one another in various contexts and how significant each is concerning the others [59]. SLW is most often found in clouds with sufficiently strong updrafts like along and over steep mountain slopes, in turbulent eddies near the mountain surface induced by local terrain, in cold Polar Regions and high-altitude clouds, especially in **cumulonimbus** and **cirrus** clouds [61]. Precipitation gauge studies have been used in statistical methods to compare seeded and nonseeded events. Then, using radar observations and snow gauge data, the spatial and temporal evolution of precipitation produced by cloud seeding is quantified. Friederich, et al. [62] discovered that when precipitation produced by cloud seeding was permitted to pass through the sensors, the gauges' measurement increased from 0.05 to 0.3 mm. Moreover in this study; the overall volume of water produced by cloud seeding varied, ranging from 1.2×10^5 m^3 for 20 minutes, 2.4×10^5 m^3 for 86 minutes, and 3.4×10^5 m^3 for 24 minutes of cloud seeding. Knowing the efficiency of cloud seeding; many countries around the world, including Australia, China, France, Greece, India, Russia, Saudi Arabia, Qatar, Turkey, and others, are conducting cloud seeding research or operations. The Beijing Weather Modification Bureau, for example, "fired 186 doses of silver iodide into the air to prompt precipitation, causing an extra 16 million cubic meters of snow to fall in the city" in November 2009. China was already investing $100 million a year in cloud seeding before the 2008 Olympics and to reduce air pollution during the 2008 Olympics. USA applies cloud seeding to mitigate hurricanes, increase the amount of snowfall at its hydropower dams by more than twofold a year, and avoid fog at airports to reduce flight delays. Hurricanes don't contain much of the supercooled water needed for cloud seeding to be effective, according to experts who found that the outcomes of this technique were dismal [63]. The benefits of cloud seeding far extend beyond the above-mentioned benefits (enhancing precipitation for hydropower generation, reducing heat wave effect, snowpack augmentation, lessening hurricanes, fog dispersal and weather modification in drought-stricken regions, etc.) into agricultural benefits (like in India, and Australia and Spain) [45]. Countries located in deserts and arid regions like Qatar and Saudi Arabia have been investing heavily in cloud seeding research and operations to improve water scarcity.

Due to its primary limitation that it can only be used within clouds that are already there, some scientists doubt that cloud seeding will be beneficial during a drought [63]. In addition, there are unsolved technical challenges including methods to deliver INPs in controlled diameter with good scattering properties. Moreover, the lifespan of aerosols as INPs is another limiting factor for the efficiency of cloud seeding. For example, tropospheric sulfur aerosols are short-lived; so as life span of delivered particles in the arctic stratosphere may be affected due to descending air. Furthermore, the effect of INP distribution and hygroscopicity is uncertain limiting the knowledge of how many tons of INP must be deployed annually to achieve the desired effect. So before any implementation, high-resolution simulations of particle dispersion away from the seeding plumes would be required to determine the spacing and frequency of flights required to build up optimal concentrations of seeding material [30]. In conclusion, the difficulty in predicting and controlling the impacts of cloud seeding makes allocating liability difficult. International, federal, and state law fail to adequately address issues related to reemerging and useful cloud seeding augmentation technologies.

Future research directions

1. It is necessary to develop ground-based measurements of precipitation intensity, type, and chemistry, and ground-based remote sensing of SLW and retrieval mechanisms for remote sensing that can track the growth of the cloud phase globally and in real-time.
2. Research might concentrate on finding or designing fungal strains that are especially useful as CCN or INP, or that release VOCs that form SOA, to optimize fungal strains for geoengineering purposes. It is possible to optimize strains for particular climate goals or settings.
3. Simulating the behavior of fungal spores in various climates, altitudes, and atmospheric circumstances can aid in the prediction of the impacts of fungal injection on weather systems, cloud formation, and precipitation patterns.
4. Exploring potential interactions between fungal spores and other atmospheric pollutants, to determine any possible effects on weather patterns or air quality
5. Examining how spore density, size, and ornamentation affect IN activity of different fungal spores.
6. Designing and evaluating efficient spore-delivering methods into clouds.

Conclusion

A growing interest in weather modification as a technique to alleviate water scarcity, address climate change, and promote agriculture is shown in the widespread usage of cloud-seeding technologies. Most countries use salt powders like silver iodide as ice-nucleating agents. Fungal spores could be an optional alternative INP for geoengineering strategies, particularly in cloud seeding and climate modification operations. The capacity to act as cloud condensation and ice nucleating particles, along with the potential to generate secondary organic aerosol formation, makes fungal spores an attractive candidate. The environmental, health, and ethical ramifications of this strategy must be carefully evaluated, and in-depth study and modeling are required to completely comprehend the benefits and possible risks alongside creating regulatory frameworks that address ethical and legal concerns.

Declarations

Conflict of interest: The authors have no relevant financial or non-financial interests to disclose. Both authors have read and agreed to the published version of the manuscript.

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