

Review

Boosting Aeroponic System Development with Plasma and High-Efficiency Tools: AI and IoT—A Review

Waqar Ahmed Qureshi ¹, Jianmin Gao ^{1,*}, Osama Elsherbiny ^{1,2}, Abdallah Harold Mosha ¹,
Mazhar Hussain Tunio ¹ and Junaid Ahmed Qureshi ³

¹ School of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, China; waqar128ahmed@gmail.com (W.A.Q.); osama_algazeery@mans.edu.eg (O.E.); 5103200333@stmail.uj.edu.cn (A.H.M.); mazharhussaintunio@sau.edu.pk (M.H.T.)

² Agricultural Engineering Department, Faculty of Agriculture, Mansoura University, Mansoura 35516, Egypt

³ Department of Mechanical Engineering, Colorado State University, Fort Collins, CO 80523, USA; junaid.qureshi@colostate.edu

* Correspondence: gaojianmin@163.com; Tel.: +86-13655282069

Abstract: Sustainable agriculture faces major issues with resource efficiency, nutrient distribution, and plant health. Traditional soil-based and soilless farming systems encounter issues including excessive water use, insufficient nutrient uptake, nitrogen deficiency, and restricted plant development. According to the previous literature, aeroponic systems accelerate plant growth rates, improve root oxygenation, and significantly enhance water use efficiency, particularly when paired with both low- and high-pressure misting systems. However, despite these advantages, they also present certain challenges. A major drawback is the inefficiency of nitrogen fixation, resulting in insufficient nutrient availability and heightened plant stress from uncontrolled misting, which ultimately reduces yield. Many studies have investigated plasma uses in both soil-based and soilless plant cultures; nevertheless, however, its function in aeroponics remains unexplored. Therefore, the present work aims to thoroughly investigate and review the integration of plasma-activated water (PAW) and plasma-activated mist (PAM) in aeroponics systems to solve important problems. A review of the current literature discloses that PAW and PAM expand nitrogen fixation, promote nutrient efficiency, and modulate microbial populations, resulting in elevated crop yields and enhanced plant health, akin to soil-based and other soilless systems. Reactive oxygen and nitrogen species (RONS) produced by plasma treatments improve nutrient bioavailability, root development, and microbial equilibrium, alleviating critical challenges in aeroponics, especially within fine-mist settings. This review further examines artificial intelligence (AI) and the Internet of Things (IoT) in aeroponics. Models driven by AI enable the accurate regulation of fertilizer concentrations, misting cycles, temperature, and humidity, as well as real-time monitoring and predictive analytics. IoT-enabled smart farming systems employ sensors for continuous nutrient monitoring and gas detection (e.g., NO₂, O₃, NH₃), providing automated modifications to enhance aeroponic efficiency. Based on a brief review of the current literature, this study concludes that the future integration of plasma technology with AI and IoT may address the limitations of aeroponics. The integration of plasma technology with intelligent misting and data-driven control systems can enhance aeroponic systems for sustainable and efficient agricultural production. This research supports the existing body of research that advocates for plasma-based innovations and intelligent agricultural solutions in precision farming.



Academic Editor: Yanbo Huang

Received: 16 January 2025

Revised: 18 February 2025

Accepted: 20 February 2025

Published: 23 February 2025

Citation: Qureshi, W.A.; Gao, J.; Elsherbiny, O.; Mosha, A.H.; Tunio, M.H.; Qureshi, J.A. Boosting Aeroponic System Development with Plasma and High-Efficiency Tools: AI and IoT—A Review. *Agronomy* **2025**, *15*, 546. <https://doi.org/10.3390/agronomy15030546>

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Keywords: aeroponics optimization; plasma-activated water (PAW); plasma-activated mist (PAM); reactive oxygen and nitrogen species (RONS); AI and IoT in aeroponics; plasma-induced nitrogen fixation

1. Introduction

The rapid growth of the world's population, estimated to reach around 9.7 billion by 2050, requires more land, water, and energy for sustainable food production [1]. Conventional farming does, however, face great difficulties like soil degradation, water shortages, fertilizer loss, and the effects of climate change. Although water supply is falling due to climate change, too much irrigation, and groundwater depletion, traditional soil-based farming is progressively unsustainable even while agriculture now consumes 70% of freshwater resources globally. More land, water, and energy are demanded worldwide for sustainable food production as the population grows. However, conventional agricultural methods have resulted in lower yield outputs, nutrient loss, and soil erosion due to excessive irrigation [1–3]. With the FAO estimating that 33% of the world's soil is already deteriorated, intensive agricultural methods also help to cause soil erosion, lower land productivity, and biodiversity loss. As a major amount of fertilizers is lost through leaching, runoff, and volatilization, contaminating water sources and raising greenhouse gas emissions, nutrient inefficiencies aggravate these problems even more. Conventional crop yields are further threatened by the unpredictable nature of extreme weather events, droughts, and irregular rainfall; so, creative ideas are even more important. The Food and Agriculture Organization (FAO) advocates sustainable agricultural methods including hydroponics and aeroponics, which provide soilless farming with up to 95% less water consumption and better nutrient efficiency, in order to meet these difficulties [4,5]. Compared to soil-based and other soilless agricultural systems, aeroponics, a soilless cultivation technique, has shown exceptional efficiency in water use, disease resistance, and growth rates [6,7]. Aeroponic systems supply nutrient-rich water to plant roots via pumps, timers, and spray nozzles, facilitating quick development and enhanced yields [8,9]. Along with these advantages, improving nutrient density, increasing nitrogen fixation, controlling microbial populations, and reducing dependency on artificial fertilizers still present difficulties. Recent innovations in plasma technology have demonstrated great promise in improving nutrient absorption, seed germination, and plant growth in both soil-based and soilless farming systems. Reactive oxygen and nitrogen species (RONS) generated by plasma treatments raise nutrient solubility, promote root development, hasten plant development, and enhance general microbial control [10–12]. While PAW has been extensively studied in soil and soilless systems, there are few studies regarding direct PAM application in aeroponics. In aeroponics, it is imperative to look at both direct plasma application (PAM) and indirect plasma therapy (PAW). Recent research shows that in aeroponics, plasma treatments improve plant growth; PAM offers a practical way to provide RONS straight to plant roots, therefore improving nutrient absorption and plant resistance [12–14]. The application of artificial intelligence (AI) and the Internet of Things (IoT) in aeroponics improves both resource efficiency and agricultural productivity. Artificial intelligence (AI) and the Internet of Things (IoT) make it possible to analyze data in a way that precisely controls critical plant growth factors like temperature, humidity, and nutrient concentration.

With the use of smart agricultural technologies, aeroponics can make real-time adjustments. For example, plasma treatments can be adjusted according to how the plants respond and how many nutrients they absorb. In addition, by predicting how crops would react to different plasma treatment parameters, machine learning algorithms improve

operational efficiency and scalability [15–19]. According to Yang et al., 2022 [20], these technologies allow precise environmental regulation, water optimization, process automation, and crop production projections. Renewable energy and automated fertilizer distribution boost production, cut labor costs, and promote agricultural sustainability [21].

This review explores the integration of plasma technologies into aeroponic systems, with an emphasis on the efficacy of nutrient uptake, plant growth, and development. Additionally, it explores how AI and IoT might improve irrigation, disease detection, nutrient delivery, and plasma-generated species. A comparative investigation of low-pressure and high-pressure misting systems is conducted, assessing their effects on nutrient absorption and plant health in relation to soil-based and alternative soilless systems. Further, it focuses on the properties and applications of plasma-activated water (PAW) in soil and soilless farming, emphasizing its effects on seed germination, plant growth, and reduced fertilizer dependency. Primary attention is paid to the generation and application of plasma-activated mist (PAM) in aeroponic systems, exploring its role in nitrogen fixation, nutrient accessibility, and plant growth. This review also focuses on the direct use of PAM with DC and RF atmospheric plasma devices. It also explores the importance of AI and IoT in boosting aeroponic farming systems, including nutrient supply, disease detection, irrigation, and plant growth. Furthermore, this review examines the role of AI and IoT in optimizing aeroponic farming systems, including nutrient delivery, disease detection, irrigation applications, plant growth, and yield, and further discusses the literature on the monitoring of PAM and plasma species using radio frequency (RF) and direct current (DC) atmospheric plasma, along with detection methods involving sensors and machine learning approaches for enhanced system optimization, as reported in previous studies. Finally, this review addresses the challenges of applying plasma technology in aeroponic systems, as well as the prospective uses of PAM in agriculture. This review intends to contribute to the future technological development of aeroponic systems and the broader agricultural sector by combining advances in plasma-assisted nutrient delivery, AI-driven optimization, and IoT-based monitoring.

2. Review Methodology

In this section, we talk about the review's approach, which includes the search criteria, study keywords, and suggestions for article inclusion and exclusion.

This analysis examines how aeroponic systems can use plasma, artificial intelligence, and the Internet of Things (IoT) to improve plant growth, water efficiency, and nutrient delivery. The examination of current advancements, limitations, and potential research directions was carried out in a methodical manner. The methodology uses a comprehensive approach to literature evaluation, which includes data synthesis, inclusion and exclusion criteria, database selection, and keyword searches. To guide the evaluation process, the following research questions were developed:

1. What developments in plasma-assisted aeroponic systems have occurred recently?
2. How is aeroponic farming enhanced by the integration of AI and IoT?
3. How do plant development and nutrient uptake become affected by plasma-activated water (PAW) and plasma-activated mist (PAM)?
4. What scaling constraints and problems arise when artificial intelligence, the Internet of Things, and plasma are combined in aeraponics?
5. How may new technologies enhance the sustainability and efficiency of aeroponic systems?

Additionally, the data used in this study came from previously published research articles. The combination of plasma, artificial intelligence, and Internet of Things applications in aeraponics has already been the subject of a great deal of scholarly research and

material. Therefore, methodically effective approaches were taken into consideration in order to assess the advanced grasp of the topic area. The following keywords were chosen for the online search in order to find relevant literature: ('High-pressure aeroponic misting' OR 'Low-pressure aeroponics') AND ('Plasma in aeroponics' OR 'Plasma-Activated Mist (PAM) in aeroponics') AND ('AI in aeroponic farming' OR 'AI-optimized aeroponic systems') AND ('IoT-based aeroponic monitoring' OR 'Smart aeroponic control systems') AND ('Plasma in soil' OR 'Plasma-Activated Water (PAW) in soil') AND ('Plasma in soilless cultivation' OR 'PAW in soilless systems') AND ('Sustainable aeroponic technologies' OR 'Advanced aeroponic farming'). Boolean operators (AND, OR) were utilized to guarantee the inclusion of relevant research while minimizing irrelevant outcomes.

The search strategy and selected keywords are illustrated in Figure 1. The China National Knowledge Infrastructure, Google Scholar, PubMed, Web of Science, Scopus, ResearchGate, AGRO, MDPI, Cambridge Journals, IEEE Xplore, Taylor & Francis, Wiley Online Library, ScienceDirect, Hindawi, and Springer were among the online scholarly databases that were extensively searched in order to obtain a thorough review. A total of 276 articles from various countries were reviewed.

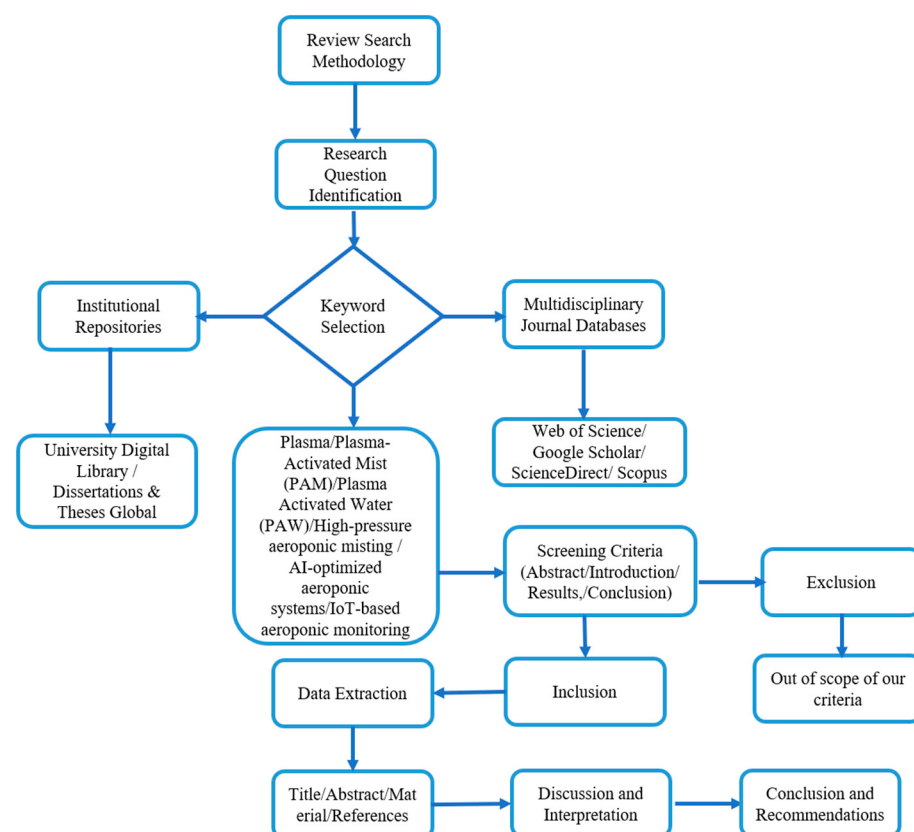


Figure 1. Proposed review methodology of the present study.

This analysis comprised published research work (articles, doctorate theses, and proceedings articles) from journals that Jiangsu University Library subscribes to and open-access publications. The literature was carefully examined and further filtered based on the criteria to include or reject literature for review proceedings after the keywords were searched. If an article had a significant relationship to the study's chosen keywords, it was directly taken into consideration. The primary dataset for this study was the information gathered by extracting and exporting the literature, including titles, keywords, abstracts, authors, and references. However, the review analysis did not include research articles

published in languages other than English. Sections of the document that were topically connected discussed the articles selected for review.

3. Results and Discussion

This section summarizes the findings on the use of plasma technology in current aeroponics, including the development and application of plasma-activated water (PAW) and plasma-activated mist (PAM) in both soil-based and soilless systems. It also investigates PAW's role in increasing nutrient bioavailability, nitrogen fixation, and microbial control in soil and soilless systems, with a particular emphasis on PAM's direct application in aeroponic systems to boost nutrient uptake and plant resilience. The section also examines the role of artificial intelligence (AI) and the Internet of Things (IoT) in optimizing plasma-assisted aeroponic systems, with a focus on RONS species generation and recognition, precision control, nutrient delivery optimization, and problems with plasma.

3.1. Aeroponics

Water scarcity is becoming an increasingly serious concern as the world's population grows rapidly. This demonstrates the importance of establishing agricultural methods that use water more efficiently and sustainably [22]. Aeroponics is a soilless growing technique that uses nutrient-rich sprays to nourish plant roots suspended in air, resulting in a considerable reduction in water usage when compared to typical agricultural methods [23]. Aeroponic systems mist nutrients onto plant roots on a regular basis using either high-pressure or low-pressure atomization to make sure they get to the roots as efficiently as possible [24]. This strategy improves nutrient uptake and root oxygenation, leading to faster growth and healthier plants, making it a highly efficient and sustainable alternative to modern agriculture.

3.1.1. Impact of Droplet Size in Low-Pressure and High-Pressure Aeroponic Misting Systems

Droplet size is crucial for plant development and health, and it has a direct impact on the efficiency of nutrient misting in aeroponic systems. Low-Pressure Aeroponics (LPA) systems use low-pressure pumps or ultrasonic transducers to produce bigger droplets of roughly 100 μm in size. While this approach provides basic nutrition delivery, it frequently results in irregular root hydration and restricted nutrient absorption. LPA systems are thus more appropriate for small-scale applications, research contexts, or educational settings [25]. On the other hand, the long-term efficacy of LPA systems may be compromised by their insufficient advanced purification and filtration capabilities. High-Pressure Aeroponics (HPA) systems, on the other hand, use high-pressure compressors to make a fine mist that surrounds plant roots and makes the droplets smaller (45–55 μm). This results in improved nutrient absorption, improved oxygenation, and enhanced plant growth. Additionally, HPA systems incorporate sophisticated filtration, sterilization, and biological support technologies, which enhance the longevity and maturation of the crop [26,27]. When compared to growing plants in soil, high-pressure aeroponics has a lot of benefits, such as higher yields, better flavor profiles, and faster plant growth rates. HPA systems have the potential to produce up to three times more than traditional soil-based agriculture when maintained under optimal conditions, according to research.

The operational efficacy of LPA and HPA systems is significantly impacted by the delivery of nutrient mist and the increase in droplet size. LPA systems use ultrasonic transducers or low-pressure pumps, which frequently result in irregular root hydration and restricted nutrient uptake, making them ideal for small-scale or instructional applications. Conversely, HPA systems employ high-pressure compressors to produce fine mists,

incorporating filtering, sterilization, and biological support technologies to improve the longevity and maturity of the crop [28].

A study by Wainwright et al. [25] created a low-pressure aeroponic system that uses centrifugal force to distribute nutritional solutions via a spinning cylinder. The device produced droplets ranging from 40 to 80 μm , which improved plant growth and nutrient absorption. It provides a portable alternative to standard aeroponics, allowing indoor growing. In comparison to soil-based approaches, the system improved root development by 25%, increased chlorophyll content by 15%, and decreased insect exposure by 30%. Particularly in relation to hairy root cultures, misting systems have been extensively investigated for their effects on oxygen absorption, root development, and general plant health. Nutrient absorption has shown improvement with high-pressure misting, using droplets between 20 and 50 μm [29]. Systems that produced smaller droplets, around 10 μm in size, significantly increased the accumulation of root biomass, according to Weathers and Wyslouzil [30]. This led to a yield of 83 g of fresh weight per liter (g FW/L) and a growth rate of 0.20% per day. Systems generating larger droplets (greater than 50 μm) often encounter waterlogging and reduced oxygen availability, which inhibits plant growth. According to sources [31,32], problems with gas exchange and liquid accumulation were the reason why the systems examined produced only 36 g FW/L and showed a growth rate of 0.08% each day.

On the other hand, studies by [33] show that droplets smaller than 50 μm improve root development and oxygen absorption, leading to growth rates of up to 0.30% each day. Additionally, research by [34] showed that smaller droplets can increase the production of beneficial growth compounds, with a yield of 50 g FW/L. According to the results, altering droplet size is essential for achieving the best possible gas exchange and nutrient delivery. According to [35], smaller droplets improve absorption efficiency and the uniformity of nutrient delivery, particularly in settings with dense root systems. Similar difficulties were faced by [31,36], which produced only 36 g FW/L and a slow growth rate of 0.08 per day as a result of problems with gas exchange and liquid buildup. Research substantiates the benefits of smaller droplets, indicating that they improve oxygen absorption and root development, achieving growth rates of up to 0.30 per day. Moreover, research showed that smaller droplets promote beneficial growth chemicals, yielding 50 g FW/L. The necessity of modifying droplet size for effective gas exchange and nutrition delivery is highlighted by these results. Lower droplet sizes frequently promote better root contact and nutrient absorption, increasing the general vitality of the plant.

3.1.2. Comparative Analysis of Aeroponic Systems with Soil and Soilless Systems

Aeroponic systems have distinct advantages over soil-based and soilless cultivation because they maximize root oxygenation through direct nutrient misting, which promotes faster growth and higher nutrient uptake. Because aeroponics exposes roots to more oxygen, it uses less water and lowers the risk of root disease than hydroponics, which immerses roots in nutritional solutions. Despite being natural, soil-based systems' scalability is constrained by problems with resource efficiency and nutrient management. According to our study [37], high-pressure aeroponics performed better in terms of yield, biomass, and water use efficiency than low-pressure, hydroponic, and soil-based systems. The WUE of high-pressure aeroponics was 72.1% greater than that of hydroponics and twice that of soil-based systems. Low-pressure aeroponics improved water use efficiency by 12.5% compared to hydroponics while producing superior antioxidants.

According to Mateus-Rodriguez et al. [38], aeroponics is better than traditional and semi-hydroponic systems for producing seed potatoes. Aeroponics saves water, chemicals, and energy while producing over 900 minitubers per m^2 and achieving high multiplication

rates (up to 1:45). According to research by Movahedi et al. [39] and Brocic et al. [40], aeroponic systems greatly increase the yields of potato minitubers. According to Brocic et al. [40], aeroponics produced 5.39 times more minitubers than conventional methods, while Marfona plants grown in aeroponics averaged 37.2 minitubers per plant, compared to 12.6 in soil. Both findings support aeroponics as a productive, disease-free technology and suggest scalability optimization. Aeroponics enhanced lettuce root growth, according to [41], with a surface area of 1550 cm²/plant and a root dry weight of 0.78 g/plant to improve shoot growth, but optimization is necessary. The aeroponic cultivation of Coffee Arabica boosted biomass yield by 1500% (16 times higher in leaves, 4.5 times in roots) and leaf caffeine content by 7170% (183 mg/kg in soil vs. 13,300 mg/kg in aeroponics) according to Wimmerova et al. [42]. Rutin was the only bioactive ingredient that increased in *Senecio bicolor*'s biomass under hydroponic conditions. Both soilless systems produced purer plants; however, they required more fertilizer and energy. Aeroponics can save up to 95% water and 85% fertilizer according to AlShrouf, 2017 [43], and can enhance production by 300% as opposed to 100–150% in hydroponics. In comparison to hydroponics and conventional irrigation techniques, aeroponics produced 11.64% more shoot dry weight and better root development, according to Khater and Ali, 2015 [44]. Aeroponics can improve nutrient uptake and increase dry biomass by 80% when compared to soil and hydroponic techniques [45]. It provides a scalable, resource-efficient solution that optimizes root oxygenation and development potential in contemporary agriculture when paired with non-thermal plasma technology.

3.1.3. Scalability and Resource Efficiency of Aeroponic Systems in Modern Agriculture

Modern agriculture has seen significant advancements because of aeroponics, which maximizes plant health and resource use. This soilless technique greatly reduces water and fertilizer usage by 98% and 60%, respectively, and does away with the requirement for pesticides, as noted by [46]. Because of improved oxygenation and targeted nutrient delivery to plant roots, the system encourages faster development and higher yields (by 45–75%) [47,48]. Aeroponics' scalability is still constrained by a number of significant issues, despite the fact that these benefits make it especially helpful in controlled environment agriculture (CEA), such as urban farms and space missions [49,50]. The infrastructure needed for high-tech aeroponic operations is a major barrier. For small and medium-sized farmers, aeroponic systems, fertilizer delivery systems, and controlled environment buildings pose serious budgetary hurdles [51]. The expenses of aeroponics can be more than what the current infrastructure can handle. Effective aeroponic operation requires technological expertise in areas such as sensor-driven monitoring, nutrient administration, and system diagnostics. Adoption may be difficult for people without technological experience because it requires trained personnel and control [5]. Moreover, aeroponic systems need a lot of energy, especially when it comes to high-pressure misting. In resource-constrained contexts, increased operational costs heighten sustainability issues, despite these systems improving nutrient absorption [9]. This issue is critical in low-income or rural areas where there are energy shortages. IoT and AI, which optimize water and energy use and automate environmental control, enhance scalability in solar-powered aeroponic systems [52,53]. Despite these obstacles, continuous technological advancements and cost-cutting measures are progressively increasing the accessibility and scalability of aeroponics, especially in space missions and urban agriculture where resource efficiency is crucial [54]. Aeroponics provides effective solutions to critical challenges in contemporary agriculture, including water scarcity, soil degradation, and food security. Figure 2 shows the main benefits of aeroponic systems, which include using less water, better nutrients, and more vertical space for plants to grow. Aeroponics is more environmentally sustainable, versatile

at many scales, improves root oxygenation, reduces disease transmission, and optimizes resource use.



Figure 2. Comprehensive advantages of aeroponic systems.

3.2. Plasma-Activated Water (PAW) Characteristics

Plasma-activated water has gained popularity in the agriculture and farming sector for its potential for producing reactive oxygen and nitrogen species (ROS and RNS), including nitric oxide (NO), hydroxyl radicals (HO), and ozone (O_3). These species are most important for healthier seed germination, disease prevention, and fast plant growth. The most common method for producing PAW is dielectric barrier discharge (DBD), which delivers high-voltage pulsed electricity (24 kV at 1.5 kHz) across electrodes separated by dielectric materials like glass or ceramics. When plasma and water interact, plasma-activated water (PAW) is produced. Research has indicated that the low energy consumption of CAP is a major factor in its effectiveness in agricultural applications, particularly in the production of PAW. Techniques such as DBD and Non-Thermal Plasma Jet Discharge (NTPJD) enhance plant development and stress tolerance and provide reactive species for seed treatment and microbial control, as shown in Figure 3 [55–57]. PAW delivery improves crop yield, nutrient absorption, and water efficiency [58]. Plasma-based AOPs play a big role in sustainable agriculture because they clean the soil and water, break down pollutants, and boost microbial activity and nutrient cycling [59,60]. A study conducted by [61] observed that reactive species, including hydrogen peroxide (H_2O_2) and nitrates (NO_3^-), in PAW are advantageous for agricultural purposes.

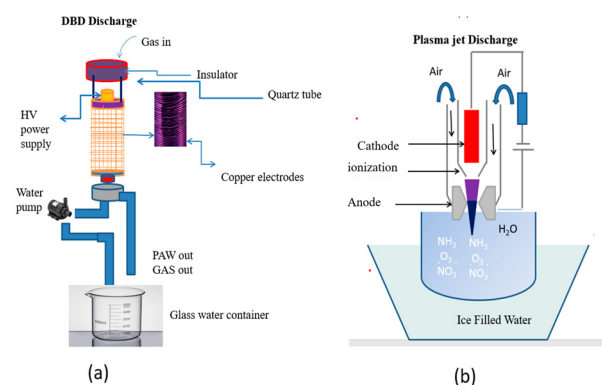


Figure 3. Schematic representation of PAW-generation models. (a) DBD discharge model; (b) jet spark model.

PAW is a fertilizer replacement that is environmentally benign and has been shown to enhance nitrogen uptake and stress tolerance. High-performance liquid chromatography (HPLC) and gas chromatography (GC) are employed to separate and quantify reactive species, including nitrates (NO_3^-) and nitrites (NO_2^-), in PAW in order to assess the efficacy of plasma interventions [62,63]. The effectiveness of PAW is assessed by measuring the redox potential and the quantities of species (e.g., H_2O_2 , NO) using electrochemical methods such as cyclic voltammetry and amperometry [64]. The precise identification of plasma-generated species is facilitated by the use of mass spectrometry, which contributes to the understanding of their role in plant growth. The influence of reactive species on seed coats and roots is further investigated using imaging instruments like Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) [65].

Various spectroscopic techniques, such as UV-vis, fluorescence, and emission spectroscopy are spectroscopic techniques that provide excellent sensitivity and real-time analysis for monitoring reactive species in plasma-treated water. Nitrite, nitrate, and peroxy-nitrite improve stress tolerance and germination by speeding up cellular processes. Their concentrations differ depending on discharge type, gas composition, and treatment duration, providing useful information for precision agricultural management [66,67]. Plasma treatments in soilless systems in Controlled Environment Agriculture (CEA) provide PAW and nutrient-enriched mist directly to plant roots, increasing crop production and nutrient uptake while using less water. Reactive oxygen and nitrogen species required for nutrition absorption are monitored using techniques such as electron spin resonance (ESR) and optical emission spectroscopy (OES). OES uses spectral wavelengths such as OH (296–310 nm), O (777–844 nm), and NO (214–270 nm) to identify specific reactive species such as hydroxyl radicals (OH), atomic oxygen (O), nitrogen atoms (N), and nitric oxide (NO [55,68,69].

Plasma-activated water (PAW) contains reactive oxygen species (ROS) and reactive nitrogen species (RNS), which collectively are referred to as reactive oxygen and nitrogen species (RONS). RONS are involved in the oxidation, antibacterial action, and promotion of plant development, as per these sources [70,71]. Reactive oxygen and nitrogen species (RONS) can be categorized as either short-lived or long-lived depending on their stability and storage circumstances. Direct detection is difficult for short-lived species, such as hydroxyl radicals ($\bullet\text{OH}$), singlet oxygen ($^1\text{O}_2$), superoxide anions ($\text{O}_2\bullet^-$), nitric oxide radicals ($\text{NO}\bullet$), and peroxy-nitrite (ONOO^-), because they decay in a matter of microseconds to seconds [66]. On the other hand, under some circumstances, long-lived species like ozone (O_3), hydrogen peroxide (H_2O_2), and nitric oxide (NO) can endure for minutes to years [72]. Because they affect chemical reactivity, plant responses, and microbial inactivation in agricultural and environmental systems, these species are essential in PAW applications. Primary short-lived radicals are formed when plasma-generated species interact with water. These radicals have a high reactivity with both organic and microbiological targets [66]. Similarly, according to these sources [72,73], secondary species have long-lasting effects on PAW's oxidative potential, pH, and bioavailability. Environmental variables such as temperature, pH, and exposure time all have an impact on the stability and efficacy of reactive oxygen and nitrogen species. Julák et al. [66] conducted research and found that cold plasma (20–50 °C) preserves reactive species by reducing recombination, while high-temperature plasma enhances their dissociation, thereby limiting their lifespan. PAW applications, such as microbial decontamination, oxidative stress induction, and nutrient enhancement in agriculture, are influenced by the dynamics. Additionally, the chemical properties and biological functions of PAW are influenced by the formation of secondary oxidants, such as nitrous acid (HNO_2), as a result of interactions between reactive oxygen species (ROS) and reactive nitrogen species (RNS).

A complex mixture of reactive species is present in PAW, which is categorized into short-lived and long-lived species based on their stability and storage conditions. Analytical techniques are very important for classifying and quantifying RONS in PAW in order to find their stability, interactions, and potential applications. Electron spin resonance (ESR) spectroscopy is frequently used to detect superoxide anions ($O_2^{\bullet-}$) and hydroxyl radicals ($\bullet OH$) utilizing spin-trap reagents like 2,2,6,6-Tetramethylpiperidine (TEMP) and 5,5-Dimethyl-1-Pyrroline-N-Oxide (DMPO). In agricultural and environmental systems, this provides information on the degree of the reactivity of these components [73–75]. Further short-lived organisms require the use of very sensitive detection methods because of their high reactivity and rapid disintegration. Ultraviolet (UV) absorption spectroscopy, which helps identify characteristic peaks associated with species that are generated from water, nitrogen, and oxygen, further expands the agricultural applications of PAW. It is generally known that short-lived organisms are hard to identify. Because the plasma discharge in the air creates extremely unstable molecules with microsecond lifetimes, direct quantification is difficult [66]. The oxidative potential and prolonged reactivity of PAW are increased by stable species like H_2O_2 and O_3 , which can persist for a considerably longer period of time [72]. These species work together to influence how well PAW boosts plant development, inhibits pathogens, and facilitates nutrient absorption. A detailed description and summary of the reactive species generated during PAW treatment, together with information on their lifetimes and related analytical detection methods, are explained in Table 1. These methods are crucial for optimizing plasma treatment parameters and for enhancing PAW applications in sustainable agriculture, water treatment, and food safety.

Table 1. Main PAW-generated RONS species and their analytical approaches.

Type	Reactive Species	Half-Life Time	Analytical Approaches	Reference
ROS	Hydroxyl ($\bullet OH$)	$10^{-9} \sim 10^{-10}$ s	ESR, BA method	[76]
	Singlet oxygen (1O_2)	4.4 μ s	ESR	[77]
	Superoxide ($O_2^{\bullet-}$)	10^{-9} s	ESR	[78]
	Hydroperoxyl ($HO_2^{\bullet}$)	N/A	ESR	[79]
	Hydrogen Peroxide (H_2O_2),	Stable	Test strips, UV-vis, FTIR	[80]
	Ozone (O_3)	s	Indigo degradation, certified kit	[81] [82]
RNS	Nitric oxide (NO)	s	ESR	[83]
	Peroxynitrite ($ONOO^-$)	10^{-3} s	Ion chromatography	[84]
	Nitrite acid (HNO_2), Nitrate acid (HNO_3)	Stable	Nitrite assay kit, UV-vis, ion chromatography	[85]
	Ammonium ions (NH_4^+)	Stable	UV-vis, ion chromatography	[10]
	Nitrous acid (HNO_2)	s	N/A	[86]

Note: The half-life time of reactive species depends on the surrounding environment. s shows the time in seconds.

3.3. Plasma-Activated Water (PAW) in Soil-Based and Soilless Cultivation

Plasma-Activated Water (PAW) has shown considerable advantages in agricultural systems, both soil-based and soilless. PAW promotes increased agricultural yields and sustainable farming practices by enhancing nutrient absorption, lowering chemical inputs, and cutting production costs. Combining PAW with soil and soilless cultivation offers a viable way to increase agricultural yields, reduce environmental effects, and guarantee the effective use of resources, as illustrated in Figure 4 [12,74,87]. Multiple plasma technologies, such as dielectric barrier discharge (DBD) and corona plasma reactors, are utilized to

produce plasma-activated water (PAW), thereby enriching nutrient solutions to improve crop performance [10].

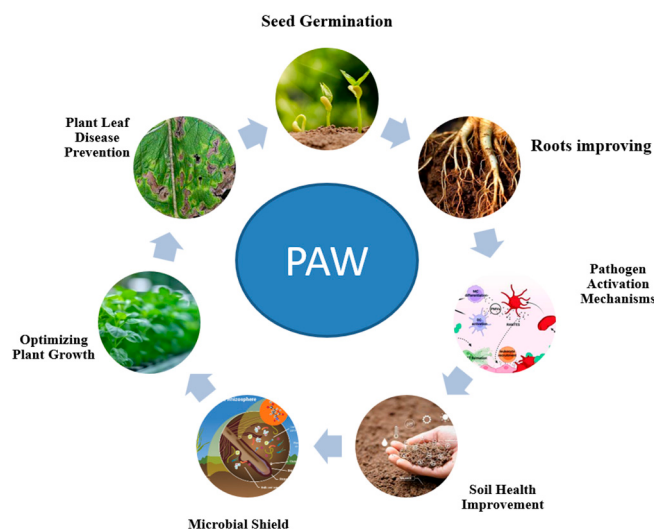


Figure 4. Benefits of PAW in soil and soilless systems.

PAW enhances soil health in soil-based agriculture and contributes to a reduction in greenhouse gas (GHG) emissions by increasing microbial activity, optimizing nutrient cycling, and decreasing dependency on synthetic fertilizers, as per these sources [88–90]. Furthermore, PAW reduces the risk of groundwater contamination and eutrophication by reducing nitrate discharge [91]. Furthermore, its antimicrobial qualities help to reduce pests and illnesses, resulting in less pesticide use and promoting overall ecosystem sustainability. The presence of reactive nitrogen and oxygen species (RONS) in plasma-activated water (PAW) increases nutritional bioavailability and strengthens plant resistance to abiotic stress and pathogens, resulting in better plant tissue health and growth [92–99].

In soilless systems, such as hydroponics and aeroponics, PAW is essential for optimizing nutrient delivery and plant development by increasing ion availability and mitigating microbial contamination, as reported by these studies [81,91,100–105]. The consistent provision of nutrient-rich solutions guarantees consistent nutrient uptake, which has the potential to reduce greenhouse gas emissions by reducing fertilizer effluent. These studies indicated that PAW is essential for the optimization of nutrient delivery and plant development in soilless systems, including hydroponics and aeroponics, by increasing ion availability and mitigating microbial contamination. The consistent supply of nutrient-rich solutions guarantees stable nutrient uptake, potentially reducing GHG emissions by reducing fertilizer runoff.

Furthermore, PAW facilitates nutrient absorption, thereby enhancing plant growth and improving root absorption efficiency, which results in increased biomass production [12,106–108]. The interaction of reactive oxygen and nitrogen species (RONS) with dissolved nutrients further enhances these effects, thereby contributing to overall plant performance.

3.3.1. Effects of Plasma-Activated Water (PAW) in Soil-Based Systems

PAW holds considerable importance in soil-based systems. The reactive oxygen and nitrogen species (RONS) engage with microbial populations and organic matter, facilitating soil chemistry and enhancing nutrient bioavailability [87]. The adoption of PAW can improve access to vital nutrients and reduce the demand for chemical fertilizers, which will reduce GHG emissions even if nutrient uptake in soil-based systems is usually slower [109,110]. Kalachova et al. [111] discovered that soil microbiomes significantly

impact plant responses to plasma treatments, opening up new avenues for sustainable agriculture. Zhou et al. [112] found that tomato seeds treated with atmospheric pressure plasma showed notable increases in germination, growth features, and fruit yield; the optimal yield was attained at a high voltage, which resulted in a 26.56% increase over untreated seeds. In soil-based tests, Sivachandiran and Khacef [109] found that plasma-activated water (PAW), which was created by exposing the water to plasma for 15 to 30 min, had an acidic pH (around 3) with moderate quantities of hydrogen peroxide (H_2O_2) and nitrate (NO_3^-). Treating radish, tomato, and sweet pepper seeds with 10–20 min plasma and irrigating with PAW enhanced germination and growth. Tomato and pepper seeds treated for 10 min and irrigated with PAW for nine days showed a 60% increase in stem length, though prolonged exposure was detrimental. Hou et al. [113] examined the impact of plasma treatment on diminishing heavy metal buildup in water spinach cultivated in polluted soil. Various plasma applications were evaluated: seed treatment with non-treated water (PTS + NTW), seed treatment with plasma-activated water (PTS + PAW), and irrigation with plasma-activated water (NTS + PAW). The results indicated that plasma therapy inhibited cadmium uptake, decreasing its bioconcentration factor (BCF) from 0.864 to 0.543, while exerting no significant influence on lead accumulation. Although plasma has the ability to alter heavy metal absorption, it did not enhance crop output. Subsequent research will refine PAW treatment parameters and evaluate its interaction with various heavy metal concentrations.

According to [114], low-temperature plasma (LTP) initially increased shoot and root growth, but it decreased vigor and germination rates from 30 to 150 days post-treatment. According to [92], PAW boosted nitrogen content in maize but negatively impacted chlorophyll and fluorescence, highlighting a trade-off between photosynthetic efficiency and nutritional enhancement. PAW promoted early development at lower concentrations and increased chlorophyll and biomass at greater concentrations in larger pots, according to [107]. PAW increases chlorophyll in many crops, demonstrating its agricultural potential. In Chinese cabbage, lettuce, and maize, it increases the production of chlorophyll, which facilitates quicker germination, better photosynthesis, and generally healthier growth [115–117].

According to Lukacova et al. [118], whose study investigated PAW's effects on maize germination and stress response, PAW pre-treatment enhanced early root growth, accelerated endodermal development, increased G-POX activity, and protected chlorophyll under stress while promoting translocation to leaves. According to [119], the long-term treatment of plasma-treated water (PTW) to barley increased its antioxidant capacity and chlorophyll content under drought stress, boosting stress resilience. Cortese et al. [120] found that plasma-activated water (PAW) raises cytosolic Ca^{2+} in *Arabidopsis thaliana* swiftly and persistently, depending on reactive species and storage conditions. PAW may improve plant development and disease resistance in sustainable agriculture. In their study, Wang et al. [121] discovered that PAW-treated wheat exhibited higher mineral and protein content, antioxidant activity, and photosynthetic pigments, which improved growth and stress tolerance. Nutrient uptake was influenced by nitrate concentration, and radicle and hypocotyl length, chlorophyll content, and leaf area were all enhanced in *Lactuca* by PAW [107]. The profile of green oak lettuce was also improved by PAW, especially when applied as an 8 kV PAW spray, which markedly increased the amounts of nitrate and total Kjeldahl nitrogen (TKN) [122]. Furthermore, PAW significantly diminished for conventional sanitizers such as hypochlorite [123]. These findings show the promise of PAW in sustainable agriculture, but more investigation is needed to completely comprehend how it affects crop maturity, yield, and nutrient density.

3.3.2. Effects of Plasma-Activated Water (PAW) in Soilless Cultivation Systems

In soilless systems, PAW has the potential to improve plant growth overall, nutrient uptake, and stress tolerance. It is thought that the RONS in PAW help nutrients dissolve and root enzyme activity, which leads to healthier plant growth and maybe even higher yields [110]. Takahashi et al. [124] found that applying PAW greatly reduced microflora in greenhouse tomatoes. Than et al. [117] used dielectric barrier discharge (Ar-N₂-O₂) to generate PAW, enhancing lettuce germination, seedling vigor, and chlorophyll content (up to 220%) with 10–20 min treatments. Longer treatments (25–30 min) had minimal additional effects, highlighting the need for optimized reactive species concentration. The varied long-term effects of PAW across crops warrant further investigation.

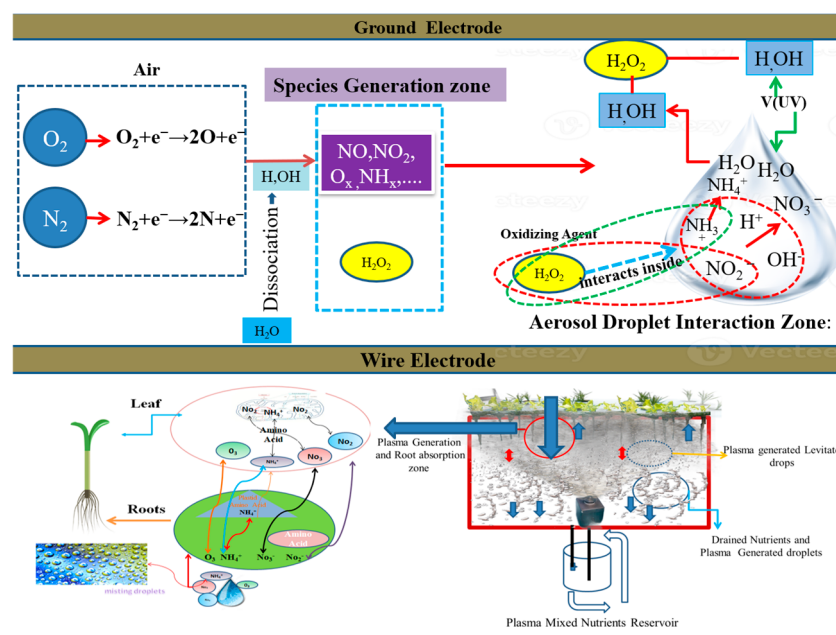
Further, Mandal et al. [114] say that PAW improves plant health and nutrient uptake because it has a lot of reactive species, like nitric oxide (NO) and hydrogen peroxide (H₂O₂). These reactive species increase plant growth and productivity by improving stress response and nutrient solution efficiency [125]. The effects of cold plasma seed priming on plant growth were examined by [126,127] on *Astragalus fridae*, showing that treating the plant with plasma and silicon dioxide nanoparticles helped the roots grow and the plant's health in general. In Abedi's study of *Cichorium intybus* and other plants, the plants grew faster, had more flowers and biomass, and were less hurt by selenium nanoparticles. By changing the seed coatings and starting up biochemical pathways, cold atmospheric and low-pressure plasma technologies help seeds sprout, grow, and deal with stress better. Depending on the plant type, treatment settings, and plasma supply, the effects vary [128,129]. According to Shao et al. [130], low-temperature plasma (LTP), particularly at an intensity of 120 W, significantly boosts the vigor and velocity of seed germination in maize. Plasma-activated water (PAW) improves plant growth, nutrient uptake, and stress tolerance, which are essential for food production. In a work by [131], they produced plasma-activated water (PAW) for nitrogen fixation using air gliding arc (GA) plasma. Although the investigation's findings indicated that PAW included hydrogen peroxide (H₂O₂), nitrate (NO₃[−]), and nitrite (NO₂[−]), these quantities rapidly decreased after five days of storage. At 48 and 72 h, PAW made with 5 L/min of airflow was most effective at making the radicle emerge and improving the germination, germination index, shoot length, fresh weight, and dry weight of rice seedlings. This means that making soluble nitrogen through GA plasma is a beneficial way to help rice seeds sprout and grow quickly after planting. Ruamrungsri et al. [12] studied the possible nitrate source of plasma-activated water (PAW) for hydroponically cultivated green oak lettuce. Plants were cultivated utilizing Hoagland's solution under three conditions: T1 (absence of nitrate), T2 (chemical nitrate), and T3 (plasma nitrate produced by a pinhole plasma jet). According to the results, T3's growth and yield were on par with T2, and its decreased nitrate accumulation reduced any possible hazards to human health and the environment. Furthermore, PAW-treated plants demonstrated elevated free amino acid concentrations, signifying enhanced nitrogen absorption efficiency. Sajib et al. [132] examined PAW as a sustainable substitute for chemical fertilizers in the cultivation of black grams. High-voltage discharge (3–6 kV, 3–10 kHz) in oxygen-deionized water was used to create PAW. The study found that higher catalase (CAT) activity, which controls H₂O₂ levels, led to improved seed germination, growth, and development. Molecular docking and VmCAT gene expression validated this process, enhancing plant development. Table 2 provides an overview of research on PAW's effects in soilless cultures, emphasizing how it affects plant growth, nutrient uptake, and stress tolerance. It illustrates how important these technologies are for raising agricultural yields and lowering chemical inputs.

Table 2. Plasma-activated water for enhancing soilless crop growth and nutrition.

Crop	Application	Importance	Significance	Reference
Radish	Plasma-activated water (PAW)	Enhanced growth and nutrient uptake	30% longer roots, 50% higher biomass	[133]
Sweet basil	Plasma-activated nutrient solution (PANS)	Growth enhancement and algae reduction	Increased growth; algae reduced by 24%	[128]
Bok choy	Plasma-treated nutrient solutions	Salinity stress tolerance and improved growth	80.5% higher dry weight	[134]
Green oak lettuce	PAW for nitrate generation	Alternative to chemical fertilizers	Plasma nitrate yields comparable to commercial nitrate	[12]
Cucumber	Plasma for decomposing allelochemicals	Growth despite chemical inhibitors	DCBA levels significantly reduced	[135]

3.4. PAM Generation in Aeroponics Systems

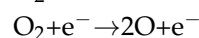
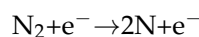
Modern aeroponic systems use plasma-activated mist generation, an innovative approach that uses plasma-induced reactive species to greatly increase nutrient availability and promote strong plant development. Radio frequency (RF) and high-voltage with low energy direct current (DC) atmospheric plasma generating devices, such as needle discharge, are used to create plasma-activated mist. These devices create ionized gases, which then create reactive oxygen and nitrogen species (RONS). These species play a crucial role in improving nutrient assimilation and promoting plant growth. Plasma-assisted technologies enhance nutrient uptake by introducing plasma-generated reactive species into aeroponic nutrient solutions, as seen in Figure 5, which reduces reliance on conventional fertilizers and simultaneously improves crop health and resilience [14,136–140].

**Figure 5.** Schematic of plasma-activated RONS generation and application in an aeroponics system.

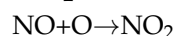
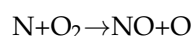
Plasma-activated mist droplets contain reactive oxygen species (ROS) and reactive nitrogen species (RNS) from air ionization during plasma discharge. In plasma devices such as DC and RF plasmas, the high-voltage discharge produces energetic particles that interact with ambient gases, resulting in the production of these reactive species. These species, particularly ROS and RNS, increase nutritional bioavailability by breaking down

complex molecules, allowing plant cells to more easily absorb nutrients. This procedure can boost plant nutrient absorption efficiency and overall development in aeroponic systems. The ionization process creates highly charged ions and free electrons, which make plasma-activated mist more reactive and improve root uptake in aeroponic systems. System design optimization improves mist–plasma interactions, enabling effective exposure to reactive species [139,141–143]. Plasma-activated water (PAW) also improves mist droplets by raising the levels of nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), and hydroxyl ions (OH^-), which helps plants grow even more. However, additional research is required to refine these methods and assess their long-term effects on aeroponic systems [19]. When these reactive species are mixed with water, they make plasma-activated mist (PAM), which is spread out in the aeroponic chamber and comes into direct contact with plant roots to help them take in more nutrients and maybe fix problems with nitrogen fixation [14,144].

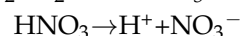
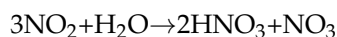
Electron Impact Dissociation: High-energy electrons break nitrogen and oxygen molecules into reactive atoms.



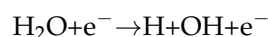
Formation of Nitric Oxide (NO) and Nitrogen Dioxide (NO_2): Atomic nitrogen reacts with oxygen, forming nitrogen oxides [145].



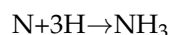
Conversion to Nitric Acid (HNO_3) and Nitrites (NO_2^-): After dissolving in water droplets, nitrogen oxides undergo further reactions to form nitrites (NO_2^-) and nitric acid (HNO_3). These chemicals exhibit excellent solubility and facilitate nutrient transport to plants.



Ammonia (NH_3) Formation: Water vapor dissociation provides hydrogen for ammonia synthesis [146].



Reactive nitrogen species can combine with hydrogen (from water vapor) to produce ammonia:



Reactive species such as nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), and hydroxyl ions (OH^-) are generated via plasma discharge, hence enhancing nutrient availability in aeroponic systems. These compounds enhance nutrient efficiency and root absorption, thereby diminishing reliance on traditional fertilizers. Henry's Law says that hydroxyl radicals change nitrogen compounds that are not easily soluble into nutrients that plants can use. Mist droplets enhance the solubility of nitrogen compounds, including nitric acid (HNO_3) and nitrous acid (HNO_2) [147,148]. New research shows that using plasma-activated nutrient mist in aeroponic systems can help plants grow by creating a clean, nutrient-rich environment. When plasma-treated mist comes into direct contact with plant roots, it makes it easier for nutrients to be absorbed quickly, which speeds up plant growth. This novel method enhances plant health while providing a sustainable substitute for conventional chemical fertilizers, hence diminishing environmental impact and resource utilization [14,136,142]. Further research has demonstrated the efficacy of plasma technology in enhancing plant development through improved nutrient delivery and sterilizing. Nitrogen-sensitive root membranes rapidly absorb plasma aerosols from

droplets generated by mist. After that, transporters make it easier for these molecules to move, which makes more nitrogen available for plant growth [149]. Enhanced nitrogen absorption is associated with deeper green foliage, elevated protein levels, and superior grain quality. Plasma-activated mist (PAM) can cause oxidative species like H_2O_2 and O_0 to build up after long-term exposure. These may harm DNA and cells, perhaps reducing growth efficacy at elevated quantities [150]. Researchers have suggested utilizing AI, IoT, and machine learning technologies for accurate regulation to enhance plasma exposure and nutritional distribution. These technologies provide the ongoing surveillance of nitrogen species, chlorophyll concentration, CO_2 levels, and mist characteristics [151,152]. To avoid nutrient imbalance, AI-driven models can change the frequency and intensity of the plasma mist on the fly, and sensor networks make it easier for nutrients to reach all areas [153]. These combined methods ensure controlled implementation and immediate supervision, which improves the efficiency of the system and the crop yield.

3.4.1. PAM in Aeroponics

Plasma-activated mist (PAM) has emerged as a viable method for surface cleaning and fog-based culture due to its capacity to efficiently distribute reactive species. PAM interacts with micron-sized droplets in high-humidity environments, allowing plasma-generated reactive species to move from the gas phase to the liquid phase. This action produces hydrated ions and acidic active chemicals within the droplets, which are critical to PAM's antibacterial efficacy. Furthermore, the size of the droplets and the discharge voltage play a crucial role in influencing the activity and effectiveness of PAM, establishing it as a versatile and efficient technology for a range of applications [154]. High concentrations of nitrogen compounds, such as nitrate (NO_3^-), were effectively generated in micro-droplets utilizing the aeroponic method, referred to as plasma-activated mist (PAM) via plasma-induced reactions. This improved the efficiency of nitrogen fixing considerably, with up to 39 times the energy efficiency of traditional plasma reactors. The solar-powered PAM system delivered nitrogen in a sustainable and renewable manner. This technique exhibited its promise as a cost-effective and eco-friendly nitrogen solution for agricultural use. It is noteworthy that PAM treatment expedited leaf emergence and increased leaf area by 30%. Furthermore, the application of plasma resulted in improvements in plant growth parameters, including stem length and leaf appearance [14].

According to Song et al. [136], ginseng sprout development and bioactive chemical content were greatly increased by plasma-treated water mist (PTWM) that was enhanced with NO_3^- , NO_2^- , and K^+ . In comparison to the untreated control, PTWM treatment raised the amount of free amino acids and ginsenosides in 25-day-old sprouts and increased shoot biomass by 26.5%. After plasma discharge, PTW developed a weak acidity that aided in nutrient uptake, demonstrating its potential as a liquid nitrogen fertilizer for ginseng. Pathogens such as *Salmonella*, *E. Coli*, and *Listeria* are rendered inactive by plasma-activated mist (PAM) by means of the reactive oxygen and nitrogen species (RONS) produced at the gas–liquid interface. Smaller droplet sizes and high discharge voltages enhance PAM's potential for disease control and agricultural disinfection [155–157]. He et al. [157] found that plasma-activated mist (PAM) efficiently decontaminated *Escherichia coli* O157:H7 on nutritional agar plates and fresh food; however, the efficacy varied depending on the variety. Kale showed the greatest reduction (3-log_{10}), followed by spinach and lettuce ($>1.5\text{-log}_{10}$), and strawberries showed the least reduction (0.8-log_{10}). When applied to stacked layers of fruit, the inactivation efficacy declined, reaching slightly over 0.9-log_{10} for spinach, kale, and strawberries, which is consistently lower than single-layer treatments. A mathematical diffusion model was used to assess PAM's scalability for industrial decontamination, with a focus on layered spinach layers. Kruszelnicki et al. [147]

conducted a study on the solvation dynamics of reactive oxygen and nitrogen species (RONS) in plasma-activated water (PAW) and mist droplets through the application of 0D and 2D modeling techniques. The findings indicated that micrometer-scale droplets, characterized by a high surface-to-volume ratio, enhance the interaction area for reactive oxygen and nitrogen species (RONS) transfer, thereby accelerating the solvation process. The study revealed that hydrophilic species (e.g., H_2O_2 , HNO_x) depend on droplet size, with smaller droplets obtaining higher in-liquid densities, whereas hydrophobic species (e.g., O_3 , N_2O) quickly saturate without diminishing gas-phase RONS. The interaction among droplet size, RONS characteristics, and plasma features is underscored by the rapid desorption of low-energy species during plasma afterglow, as well as the impact of plasma non-uniformity on solvation rates. Plasma-activated mist (PAM) technology augments aeroponic systems by facilitating seed germination, promoting plant growth, enhancing nutrient absorption, and bolstering disease resistance. PAM is a sustainable and efficient technique for contemporary farming because reactive species like auxin and gibberellic acid promote early growth, increase nutrient absorption, and lower microbial activity [109,127,158].

3.4.2. Direct Application of PAM

In aeroponic systems, atmospheric-pressure plasma discharge enhances nitrogen fixation and root productivity. Through plasma-treated water (PAW), dielectric barrier discharge (DBD) plasma increases crop shelf life, decreases microbial contamination, and improves nutrient bioavailability [159]. Additionally, O_3 ozone produced by DBD improves seed germination and increases nitrogen availability, which promotes plant growth [160,161]. In nutrient solutions, low-energy DC atmospheric plasma generating device systems produce reactive oxygen and nitrogen species (RONS), such as NO_2 , NH_3 , O_3 , and H_2O_2 , which promote nutrient breakdown and boost bioavailability [162]. Reactive species produced by plasma, namely $\text{H}_2\text{O}_2\text{aq}$ and HOONOaq , improve plant metabolism, which raises nutrient uptake and total crop output [147,148]. By using plasma-activated mist (PAM) for continuous and scalable in-flow nitrogen fixation, plasma-based nitrogen fixation offers a sustainable alternative. Plasma-assisted oxidation techniques generate reactive nitrogen species within micron-sized water droplets, allowing aeroponic systems to deliver nitrogen directly to plant roots and enhance nutrient absorption efficiency. PAM is a viable option for sustained nitrogen fixation in aeroponics due to the increased efficiency achieved through energy concentration in droplet micro-reactors, which can utilize up to 39 times more energy than traditional plasma reactors [14,144].

According to Li et al. [140] Plasma-based nitrogen fixation in aeroponics is significantly improved by a cascade discharge system that uses dielectric barrier discharge (DBD) with a three-stage spark discharge. This system changes atmospheric nitrogen (N_2) into water-soluble nitrogen molecules, especially N_2O_5 , by reacting NO and NO_2 with ozone (O_3) made by DBD. By achieving a high nitrogen yield while using less energy, this technique makes aeroponic cultivation more effective and expands the use of dispersed plasma nitrogen fixation in soilless agriculture. High-pressure ultrasonic nozzles (HPUN) and low-energy plasma systems have been proposed to work effectively to provide a self-sustaining plasma source. This combination may improve nitrogen fixation, nutritional absorption, and water efficiency, which could result in longer-lasting, healthier crops. Furthermore, compared to high-energy plasma therapies, plasma-induced oxidative stress may increase plant resistance to damage while using less energy [14,139,141,142]. Plasma-assisted aeroponics has the potential to change agriculture because it improves the delivery of nutrients, the uptake of nitrogen, and the oxygenation of roots.

The direct application of plasma-activated mist to the root zone has been documented in multiple studies as a successful method for improving nitrogen fixation, sterilization, and microbial regulation. This paper provides a hypothesis for the creation of a cost-effective plasma device that may generate equivalent reactive species based on these findings. RF and DC atmospheric plasma-generating devices have undergone extensive study for similar applications [138,140,160,161]. This review suggests that integrating RF and DC atmospheric plasma-generating devices into aeroponic systems could significantly enhance nutrient absorption, as illustrated in Figure 6. Research on nebulizers and fine foggers, which was previously studied by researchers, indicates that the fine mist generated by aeroponic nozzles is essential for the root absorption of plasma-derived species [14,141,160]. If aeroponic systems can make this kind of mist, these reactive species could combine with droplets in a way that makes it easier for nutrients to get to plant roots. Additionally, adding plasma devices to high-pressure ultrasonic nozzles (HPUN) could make plasma-assisted aeroponics self-generating and work better, providing a new way to improve plant growth and nutrient uptake.

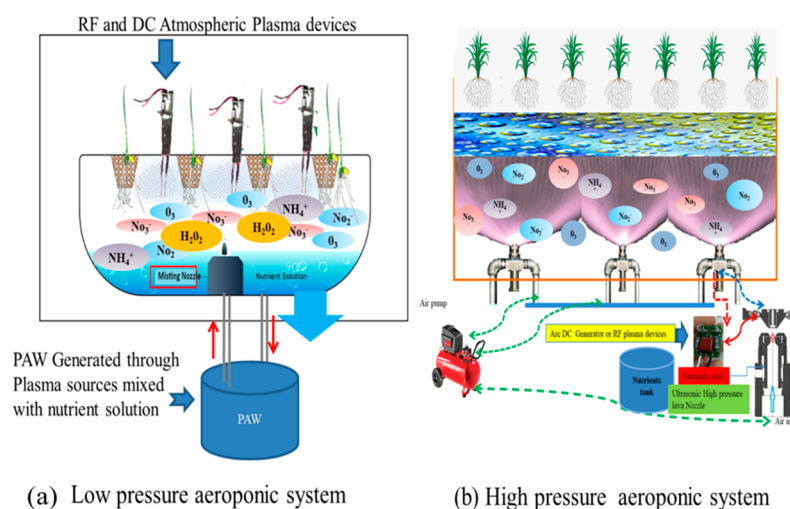


Figure 6. (a) Direct application of RF and DC plasma near the root zone. (b) Self-generated plasma species via high-pressure nozzles in aeroponics.

3.5. Impact of Control Systems, AI, and IoT in Aeroponic Systems

The implementation of artificial intelligence (AI), the Internet of Things (IoT), and machine learning (ML) has significantly altered the management of plant growth conditions and resource utilization in agricultural systems, particularly in aeroponics. AI-powered control systems enable the real-time monitoring and management of critical environmental parameters, such as temperature, light intensity, humidity, and nutrient concentrations. Predictive analytics and optimization techniques in machine learning models are essential for enhancing these parameters. The optimization of fertilizer distribution and misting cycle has been accomplished through the application of Reinforcement Learning (RL). Reinforcement learning enhances plant health and optimizes growth efficiency through its iterative learning process.

Additionally, AI systems that analyze sensor data and recognize images can spot early signs of plant stress and disease detection, allowing for preventative actions. Neural networks (NNs) and support vector machines (SVMs) are frequently used to identify these indicators. Many studies have been conducted on AI-based disease detection [163–167], fertilizer and irrigation control automation [168–171], plant development state recognition [172], and yield prediction [173–176], all of which help to improve the sustainability and efficiency of aeroponic systems. These developments promote more ecologically friendly

farming methods by reducing resource use and improving aeroponic system precision and scalability. Despite advancements, obstacles persist, such as elevated expenses, intricate systems, and data accuracy, which impede the extensive implementation of these technologies. However, it is anticipated that continued advancements in cloud computing, the Internet of Things (IoT), and increasingly complex artificial intelligence (AI) models will overcome these obstacles and improve aeroponic system performance even more [177]. A significant breakthrough in agricultural innovation is represented by the combination of advanced control systems, artificial intelligence, and machine learning in aeroponics. As illustrated in Figure 7, IoT-based smart farming with cloud-based monitoring and aeroponic control systems improve precision in nutrient delivery, environmental regulation, and real-time data analysis, maximizing crop growth and resource efficiency.

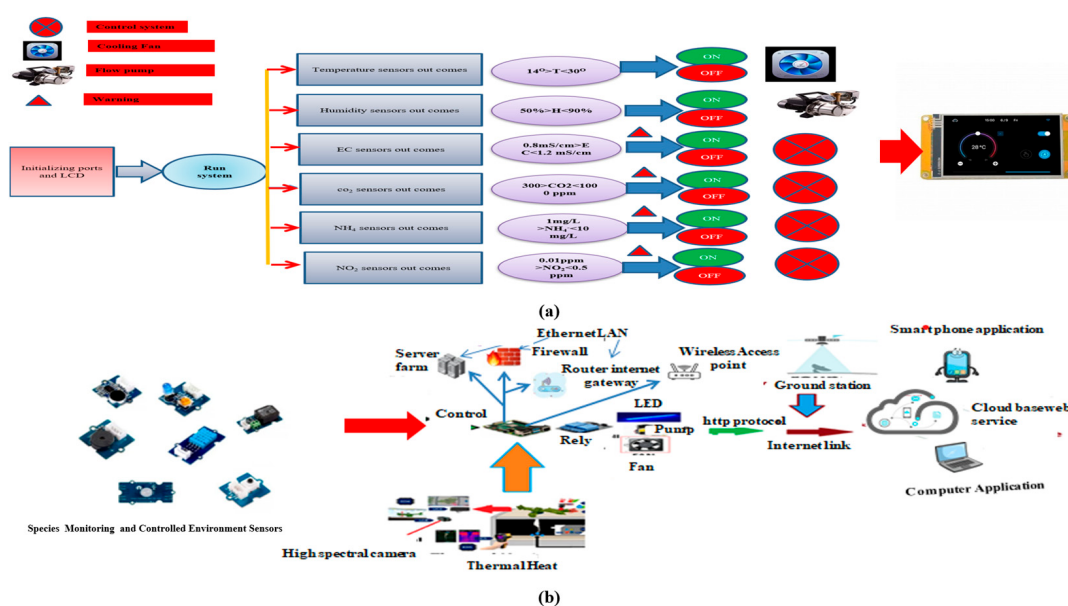


Figure 7. (a) Automatic control system, (b) integrated IoT-based smart farming system with cloud-based monitoring.

Nutrient levels, pH balance, humidity, temperature, and light exposure are just a few of the critical environmental factors that these technologies make possible to precisely control for the best plant growth [17,178,179]. In addition to raising crop yields and quickening growth rates, this strategy improves resource efficiency and reduces environmental effects, all of which support sustainable farming methods [180]. Large volumes of data on plant growth, weather patterns, and nutrient levels can be processed using data analytics. This makes it possible to predict the best growing conditions, which helps farmers maximize the productivity of their aeroponic systems [181,182].

By analyzing sensor data, machine learning algorithms can forecast growth paths, identify possible problems early, and automatically modify operating parameters, which helps to improve cultivation techniques and maximize resource utilization [183,184]. Growers around the world may increase agricultural productivity, enhance crop quality, and maintain their financial stability and environmental sustainability by integrating these technologies seamlessly [185]. IoT, AI, and LED technologies combined with aeroponics have the potential to revolutionize the sustainability and efficiency of agricultural output. These technologies provide the exact regulation of essential development parameters, including temperature, humidity, and fertilizer misting, while also offering real-time environmental surveillance. Because it increases crop output, growth rates, and nutrient uptake, aeroponics is a possible alternative for urban and space-constrained agriculture.

Studies combining sensor-based aeroponic systems with IoT and AI technologies to enhance crop quality, growth, and fertilizer efficiency are compiled in Table 3. These studies show how AI-powered control systems and IoT-enabled real-time monitoring may enhance environmental conditions, automate nutrient distribution, and cut down on resource waste. Numerous crops are studied, showing how these systems increase growth rates, yield quality, and nutrient uptake while adapting to shifting agricultural demands. The studies were selected because they employed cutting-edge techniques backed by peer-reviewed publications from the past ten years, including feedback-driven control loops, machine learning algorithms, and predictive analytics.

Table 3. Overview of advanced IoT-based technological integration in aeroponic systems for enhanced crop cultivation.

Plant	Treatments Used/Technology	Technology	Key Findings and Performances	References
Maize	IoT, temp and humidity control, real-time monitoring	IoT-based sensors	Automates nutrient delivery, reduces labor, optimizes resources, real-time alerts	[186]
Crop not specified	Irrigation, nutrient, and climate control	IoT, Raspberry Pi	IoT-based auto-monitoring and control	[187]
Tomato (<i>Solanumly copersicum</i>)	Climate, water, evapotranspiration control	IoT for Evapotranspiration Monitoring	Uses microcontroller for evapotranspiration	[188]
Basil (<i>Ocimum basilicum</i>)	Nutrient misting, humidity control, real-time monitoring	IoT-based monitoring system	Real-time data collection and control	[52]
Green leaf lettuce	Nutrient misting, temp, humidity, irrigation control	Arduino-based IoT system	40% increase in leaves, 400% in root growth	[189]
Mustard greens (<i>Brassica juncea</i>)	pH control, automated irrigation, climate control	IoT-based system	Optimizes temperature and humidity for growth	[190]
Pakcoy (<i>Brassica rapa</i> . L.)	Climate control, nutrient automation, real-time analysis	IoT for smart farming	Regulates growth and mist environment	[191]
Pakcoy (<i>Brassica rapa</i> . L.)	NodeMCU, DHT22, TDS sensors, Blynk app	NodeMCU, Blynk	Superior sensor precision, similar growth to control group	[192]
Crop not specified	Temp and humidity control, LED lights, IoT-based monitoring	IoT-based system	Enhances growth and stabilizes conditions	[193]
Lettuce	Misting, sealed environment for water and nutrient delivery	Smart farm system	Reduces water usage, optimal conditions for urban environments	[194]
Lettuce	IoT sensors, machine learning for automation	IoT sensors, machine learning	Improves yield prediction and automates growth	[195]
Crop not specified	Multi-variate regression, ResNet-50 for growth estimation	Machine learning, neural networks	Multi-variate regression best for biomass, ResNet-50 for growth rate estimation	[196]
<i>Ipomoea reptans</i>	LED lighting, IoT control for temp, humidity, light	Wemos D1 mini, Thing Speak	Controlled temperature and improved growth quality	[179]

Future Prospects of AI and IoT-Driven Plasma Control in Aeroponics

The use of low-energy direct plasma devices, such as radio frequency (RF) or direct current (DC) atmospheric plasma, generates an environment rich in reactive plasma species in aeroponic systems. Plasma-activated water (PAW) can be utilized in mist form, facilitating the generation of plasma species within the aeroponic system [140,144,149,197]. Future advancements in sensor technologies have the potential to improve the efficiency and effectiveness of the system through the monitoring and control of these plasma species. Figure 8 shows that many studies have looked into how to find species using gas sensors,

spectrophotometry, and optical emission spectroscopy (OES). Specifically, gas sensors like MQ-137 and MQ-131 have been widely used for detecting ammonia (NH_3), (O_3), and other reactive species. Lai et al. and Tozlu [198,199] created ensemble recurrent neural networks (RNNs) that can use cheap IoT sensors to find CO , O_3 , and NO_2 . They obtained excellent results by training the models over and over again. They used an Artificial A-gae Algorithm (AAA)-based Elman Neural Network (ENN) model to make ozone (O_3) detection and real-time monitoring even better. This suggests that AI can be employed for monitoring atmospheric plasma. Rahardja et al. [200] utilized Support Vector Regression (SVR) and Gradient-Boosted Decision Trees (GBDT) to identify pollutants in agricultural environments. The sensitivity and specificity for the classification of NO_2 and NH_3 have been improved.

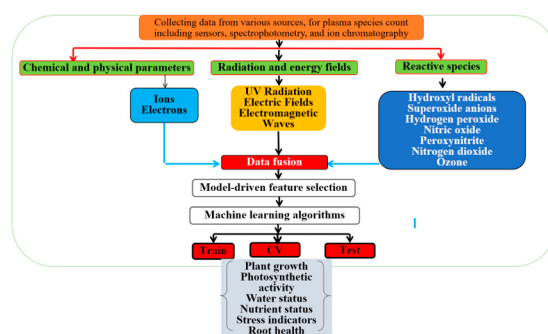


Figure 8. Conceptual model for AI-powered plasma species identification and tracking in aeroponic systems.

Li et al. [201] employed a graphene–polyaniline sensor array alongside machine learning, achieving over 99% accuracy in monitoring NH_0 and NO_2 . The study showed that combining nanomaterial-based sensors with AI algorithms improves the ability to identify species in plasma-treated environments in real-time. Bruno et al. [202] examined selectivity challenges in metal-oxide-semiconductor (MOX) sensors by integrating artificial neural networks (ANNs). This facilitated the process for farmers to locate ammonia. Further, Mahapatra [203] conducted a study on developments in AI-driven gas sensing, highlighting improvements in accuracy, safety, and efficiency through real-time monitoring and predictive diagnostics. The integration of AI with nanomaterials enhances sensitivity and selectivity, which in turn optimizes environmental and health management.

Chen et al. [204] used Optical Emission Spectroscopy (OES) and machine learning to study Atmospheric Pressure Plasma Jets (APPJs) and were excellent at identifying species. Chan et al. [205] showed that cold atmospheric plasmas (CAPs) could identify tissues non-invasively with 99% accuracy. This shows that similar AI-based monitoring systems could be useful. Özdemir et al. [206] employed ML-based plasma flame analysis to monitor cold plasma spraying. This gave them information about how stable and effective plasma is. AI-driven plasma species detection was also demonstrated by [18] in optimizing H_2O_2 sensing. The study conducted in [207] presents an IoT-based air quality index (AQI) system that utilizes Random Forest, Regression, K-Nearest Neighbors (KNN), and Long Short-Term Memory (LSTM) models, demonstrating advancements in the field of environmental monitoring. Tozlu [199], in his study, developed an electronic nose for the detection of methanol, achieving an accuracy of 85.88%, thereby demonstrating the capabilities of electronic sensing technology. Li et al. [201] mixed polyaniline and graphene oxide to make sensors that can find NH_0 and NO_2 in mining operations. These sensors are designed for wearability and remote monitoring. Listyarini et al. [208] created a GSM-based system for monitoring ammonia levels, while [209] introduced an NB-IoT air quality monitoring device for real-time environmental assessments. Petric et al. [19]

created an ammonia detection system based on Arduino and Python-based analytics. This system enables the customizable real-time monitoring of plasma-generated species. Lai et al. [198] enhanced pollution monitoring through the implementation of an ensemble machine-learning model that integrates LSTM, GRU, Bi-LSTM, and Bi-GRU architectures. Scalability was added to the method. Maulini et al. [210] enhanced aquaponics water and fertilizer management using Internet of Things sensors, while Mohammed et al. [211] developed an Arduino-based air quality control system. Furthermore, a range of machine learning models—including BPNN, DT, GBM, CNNs, SVM, RF, autoencoders, and XGBoost have been widely used to assess plant health by looking at important variables like growth rates, photosynthetic activity, stress levels, water availability, nutrient status, and root health. These models offer real-time monitoring of how environmental factors affect plant productivity [17,212–214].

According to the studies, sensor, AI, and machine learning technologies have all been successfully used for real-time plasma species monitoring in a variety of applications. These methods provide significant promise for improving plasma-assisted nutrition delivery, despite the fact that they have not been widely used in aeroponic systems. Through the precise monitoring of plasma-generated reactive species, the integration of gas sensors, spectroscopic methods, and AI-based analysis has the potential to increase system efficiency and encourage plant development. To guarantee the accuracy, stability, and long-term viability in aeroponic environments, issues including sensor calibration, adjustment to dynamic plasma conditions, and the operational costs related to gases utilized in plasma formation must be resolved.

3.6. Challenges and Optimization of Plasma in Aeroponics

System integration, cost control, and energy efficiency optimization are the difficulties in scaling plasma for aeroponic systems. The potential for plasma-based nutrient enhancement and sterilization exists; however, large-scale implementation faces challenges due to elevated power consumption and operational expenses. Many studies have shown that by adopting low-energy DC or RF atmospheric plasma-generating systems, the total cost can be much lowered as these systems do not require extra gases for operation. Feasibility is greatly affected by the choice of plasma gas; for example, air is about \$0 [88], whereas helium costs \$636,000–\$9,096,000 per 1000 h, nitrogen \$9000–\$72,000, and oxygen \$18,000–\$144,000. In [215], they demonstrated a dielectric barrier discharge (DBD) reactor that broke down N,N-dimethyl formamide for 0.11 EUR/kWh and saved 13.2 mg/kJ of energy. Energy demands are also directly impacted by electrode arrangement and power scaling; research indicates that scaling NTP from the lab to an industrial scale can quadruple the power requirements. Gao et al. [14] discovered that the ns plasma peak power ranged from 160.5 to 231.1 kW, with an energy efficiency of 47.79 MJ/mol and an average power of 3.85 W. Different studies have shown that the system can work in different ways, with energy efficiencies of 1900 MJ/mol [148], 1040 MJ/mol [197], and 96 MJ/mol [216]. Increasing plasma power, say, from 18 W to 42 W, makes NO₁ production better but also dramatically raises energy costs, since 210 MJ/mol of NO_x is needed instead of 150 MJ/mol [140]. Even though complex setups like DBD + 3-stage spark discharge make things work better, voltage, frequency, and gas flow rates still need to be tweaked more to find the best balance between energy use and nitrogen fixation efficiency for long-term agricultural uses. Enhancements in cost viability and energy efficiency are also necessary for the scalability of NTP systems. Precision farming and automation are becoming more and more important in sustainable agriculture, yet energy-intensive DBD devices and plasma jets are still expensive. NTP can become more cost-effective by using green energy sources and increasing plasma system efficiency [217,218]. Furthermore, by

incorporating it into irrigation systems, plasma-activated water (PAW) can lower chemical input costs [217]. NTP has demonstrated the ability to improve productivity and manage infections sustainably in aquaponics [88]. These things show how important it is to have plasma configurations that are both cost-effective and make the best use of energy, gases, and discharge parameters while also using renewable energy sources to help widespread adoption in agriculture.

4. Conclusions

The review examines previously published research on plasma technologies, plasma-assisted aeroponic systems, artificial intelligence (AI), and Internet of Things (IoT) applications, with a special focus on the production and utilization of plasma-activated water (PAW) and plasma-activated mist (PAM). These methods have shown a lot of promise for making it easier for plants to take in nutrients, fix nitrogen, and control microbes in both soil-based and soilless farming systems. PAW, for example, has been widely employed in both soil and soilless systems to improve plant growth by increasing nutrient availability and reducing reliance on traditional fertilizers. Meanwhile, PAM has shown potential in aeroponics, where direct application can increase nutrient delivery and reduce nutritional deficiency. The reactive species in PAM not only change metabolic processes but also help fix nitrogen, which makes plants stronger and helps them grow.

Furthermore, this review underlines the significance of AI and IoT integration in controlling environmental variables such as misting cycles, nutritional concentrations, and plasma species. AI-powered models are especially promising for predicting plant reactions to plasma treatments, optimizing nutrient blends, and improving overall system efficiency, which can minimize resource usage while increasing crop output.

The review also addresses significant issues such as energy consumption, cost-effectiveness, and the effects of plasma treatment on plant physiology. Despite the enormous potential for sustainable agriculture, further study is needed to improve the efficiency and scalability of PAW and PAM in commercial aeroponics systems. Recent years have seen remarkable advancement in the development of plasma applications, AI models, and IoT aeroponics solutions. Despite these major gains, some key challenges remain, particularly in optimizing plasma treatment settings, scaling up plasma generation for large-scale commercial systems and assuring the longevity and stability of sensors in dynamic plasma environments.

By identifying these gaps, we are hoping to help researchers, practitioners, and policymakers improve the economic viability of plasma-assisted aeroponic systems. Despite the challenges, we believe that ongoing advancements in plasma-based technologies, together with AI and IoT, will pave the way for more sustainable and resource-efficient farming approaches.

We hope the findings of this study will encourage further innovation and interdisciplinary collaboration to increase the use of plasma-based technologies in agriculture, resulting in more sustainable and energy-efficient food production systems around the world.

Author Contributions: Conceptualization, W.A.Q. and J.G.; Methodology, W.A.Q.; Validation, J.A.Q. and A.H.M.; Formal Analysis, W.A.Q.; Writing—Original Draft Preparation, W.A.Q.; Writing—Review and Editing, W.A.Q., O.E., A.H.M., M.H.T. and J.A.Q.; Visualization, W.A.Q. and O.E.; Supervision, J.G.; Project Administration, J.G.; Funding Acquisition, J.G. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge that this work was financially supported by the National Natural Science Foundation of China Program (Grant No. 51975255) and the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (Grant No. PAPD-2018-87).

Conflicts of Interest: The authors declare no conflicts of interest, financial or personal, that could have influenced the research or outcomes presented in this paper.

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