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Sustainable and safer indoor farming of produce using new technologies: challenges and opportunities

Introduction

According to a report by the Food and Agriculture Organization of the United Nations (FAO), by 2050 agriculture will need to produce 60% more food to feed the projected 9.3 billion population (FAO, 2014). With advances in agriculture such as high yielding varieties, chemical fertilizers and pesticides, and optimized irrigation, world food production has increased threefold in the last 50 years, with only 12% increase in the farmed area (FAO, 2014). The report also points out that while the food supply is growing, the current agricultural practices are inadequate to meet the future growing needs and are unsustainable. In addition, there is very little scope for expanding agricultural farmland; 80% of the projected increase in the food supply has to come from the existing agricultural land (FAO, 2014). Thus, there is a need to increase the food supply by increasing agricultural production with optimum land use, conservation of water, and with minimal use of fertilizers and pesticides (UNEP, 2012). Current challenges associated with traditional agriculture include dependence on many natural resources, fertilizers and pesticides residues, and exposure to pathogen contamination. Pathogen contamination may occur in an open farming system from soil, irrigation water, inadequately composted animal manure, dust, insects, birds, and, wild and domestic animals. Pathogen contamination is a big concern especially in fresh produce, which is usually consumed without any processing or kill step. Additionally, post-harvest losses due to short shelf-life of fresh produce do not help bridge the gap between consumer demand and supply. Indoor farming with soil-less production may be able to bridge this gap because it is efficient compared to traditional agriculture, uses natural resources efficiently, and provides opportunities for sustainable and safer ways to grow selected fresh produce.

Indoor farming or controlled environment agriculture (CEA) can be termed as ‘the future fresh produce manufacturing system’; a farming system that will grow fresh produce sustainably with minimal land and water use, one that will use high-end technology and automation, and will provide new opportunity for advancing food safety and traceability compared to conventional agriculture practices.

In CEA, the crops are grown in an enclosed space with or without soil, while providing optimum conditions such as nutrient levels, artificial light exposure, temperature, relative humidity, carbon dioxide (CO_2) around the leaves, oxygen (O_2) around the roots and shoots (for respiration), and other environmental conditions (Rorabaugh, 2015). Some indoor farming methods such as greenhouse have been in use since 1920 (Cosgrove, 2018), while some methods such as hydroponics, aquaponics, and aeroponics that may include vertical farming, are relatively recent. Indoor farmers are using high-end technology including LED lights, automation, robotics, informatics, and data science, for sustainable farming. Unique selling proposition (USP) of indoor farming includes less use of water, less use of pesticides, automation, higher crop production per unit area, shorter supply chain if grown in an urban setting, less dependence on natural climate, and improved food safety (Sworder, 2019). However, the challenges and limitations remain in terms of high cost, labor, and energy requirements. It is hoped that with further research and developments, ways to overcome some of these challenges will be found.

In this bulletin, various indoor farming methods, their current status, the technologies involved and their future prospects are reviewed. In particular, the focus is on sustainable plasma technology and its scope in CEA for improved growth, yield, and safety of fresh produce.

Soil-less indoor farming methods

In soil-less indoor farms, crops are grown using various methods such as hydroponics, aquaponics, and aeroponics. In these methods, crops are grown either in traditional green-house ways or in vertically stacked racks inside an urban structure (vertical farming) or in a shipping container (container farms).

Hydroponics

Hydroponic systems rely on mineral solution enriched with essential plant nutrients instead of soil to achieve optimal plant growth. A hydroponic system may use an aggregate medium such as sand, gravel, perlite, rockwool, or coco coir to support the roots. Hydroponic setups work on the basis of osmosis, pH, and controlled environment to promote photosynthesis (Mohammed, 2018). Hydroponic systems can be categorized depending on how the nutrient solution is provided to the plants. Common setups include drip, wick, nutrient film technique, deep flow technique or water culture, and ebb and flow (Rorabaugh, 2015). In drip systems, the nutrient solution is fed to each plant individually through spaghetti drip lines. Wick system is a simple hydropic system in which in a wick is placed in a reservoir containing nutrient solution. The plants placed in another container above the reservoir draw nutrients from the wicks by capillary action. Nutrient film technique uses a tilted channel, which takes advantage of gravity for a continuous flow of nutrient solution as a film. The water is recirculated from reservoir located below the channel. Deep flow technique or water culture employs tanks lined with plastic, where plant roots are submerged in a well-oxygenated nutrient solution 24/7 (Rorabaugh, 2015). In the ebb and flow system, plants are anchored in an inert medium and receive intermittent nutrient solution flow from a nutrient reservoir using a pump.

Vegetables, flowers, houseplants, and medicinal plants are being grown on a commercial scale using hydroponics. Some examples of hydroponic vegetable growers and their products in the US include Nature Sweet, Arizona– over 300 acres throughout USA (tomatoes); Village Farms, Texas – over 232 acres (tomatoes, cucumbers, and peppers); and Houweling Nurseries, California – over 125 acres (tomatoes and cucumbers) (Rorabaugh, 2015). In addition to commercial practices, some local communities have successfully used hydroponics technology to grow crops using abandoned urban structures to address local food security. Some successful examples community based hydroponics farming include Gotham Greens, New York, MI Urban Farming Initiative, Michigan, the Farm on Ogden in the Lawndale neighborhood of Chicago (Marston, 2018; Rorabaugh, 2015) and StartUpRoots, Israeli NGO that runs hydroponic farming projects in Israeli schools and a Jewish day school in America (https://www.startuproots.org.il/).

Recently, home produce growing systems are also attracting customers. Some examples include Canadian startup Grobo, USA based LEAF, Israel based company Seedo, and Greece based City Crop. Grobo Waterloo, Canada uses a modern hydroponic home organic produce growing system that can be controlled using an app (https://www.grobo.io/). LEAF located in Boulder, Colorado, USA uses smartphone controlled hydroponic growing system for variety of vegetable and herbs (https://www.getleaf.co/). Israel based company Seedo provides a home growing system for vegetables, herbs, and flowers (https://www.seedolab.com/). City Crop's indoor garden box with controlled climate can be used to grow vegetables, herbs, and fruits (https://www.citycrop.io/)

Aeroponics

In the aeroponics system, plants are grown with roots exposed to air. Plant roots get nutrients from the nutrient-filled aerosolized mist that they are exposed to. The National Aeronautical and Space Administration (NASA) developed aeroponics in the 1990s and defined the term aeroponics as "growing plants in an air/mist environment with no soil and very little water" (Birkby, 2016). Aeroponics techniques can result in saving 90% water compared to an efficient hydroponic system (Birkby, 2016). However, commercial applications of aeroponics are scarce due to high hardware investment and maintenance involved. Mist droplet size and the frequency of the misting are two important factors influencing the effectiveness of an aeroponic system. Maintaining a smaller droplet size of mist for it to stick to roots for better nutrient absorption is a challenge. Regular maintenance skills are needed for keeping the miniature high-pressure, mist generating nozzles clean as they may get clogged frequently (VeggieHarvest.com, 2019).

There are a few examples of successful aeroponics based fresh produce businesses. NASA (USA) funded a company AgriHouse from Berthoud, Colorado, for rapid closed-looped food production systems which was one of the first farm-based on aeroponics (Mahesh, Minhas, & Razak, 2016). AeroFarms in Newark, New Jersey is one successful recent example of aeroponics indoor vertical farming with 70,000 sq. ft. facility. They have the capacity of growing 2 million pounds of microgreens such as baby spinach per year. They have optimized a patented aeroponic growing system for faster harvest cycles, predictable results, superior food safety, and less negative environmental impact (https://aerofarms.com/technology/). Neofarms, a start-up based in Hannover, Germany makes household refrigerator size aeroponics vertical farm systems to grow produce at home (https://www.neofarms.com/). CombaGroup, Molondin, Switzerland has developed a mobile aeroponics irrigation system to the culture plants in air or mist environments (https://www.combagroup.com/). Using an optimized soilless culture systems, combined with a fully-controlled environment, they are able to grow lettuce and aromatic plants in a clean pesticide free environment.

Aquaponics

Integration of hydroponics with aquaculture where nutrient-rich effluent from fish tanks is used to fertigate crops hydroponically is known as aquaponics (Diver, 2006). Aquaponics relies on the integrated relationship between the animals and the plants, and requires skills to simultaneously manage the production of two different agricultural products, namely fish and crops (Alshrouf, 2017; Diver, 2006). Compared to hydroponic systems, in which the cost of nutrients fed to plants is high, in aquaponics nutrients are provided by the nutrient-rich wastewater from fish tanks. The fish are sustained using fish feed which is cheaper compared to the nutrient solution (Alshrouf, 2017). Plants in turn, clean the wastewater so that it can be recycled for growing fish (Birkby, 2016). This practice renders aquaponic farms completely organic (Alshrouf, 2017). As opposed to constant testing of the hydroponic solution to ensure availability of nutrients, in aquaponics only a few things need to be monitored such as pH and ammonia levels once a week, and nitrate levels once a month (Alshrouf, 2017). The fish waste used in aquaponics is not a food safety concern as it originates from cold-blooded animals and does not harbor the same pathogens as warm-blooded animals (Nelson, 2014).

Some successful commercial examples of aquaponics farm include Edenworks, Brooklyn, New York, a rooftop aquaponics operations producing microgreens and tilapia (https://edenworks.com/), Lucky Clays Fresh, Norwood, North Carolina, growing lettuce, fish, and shrimp (https://luckyclaysfresh.com/), GrowUp Urban Farms, London, UK (https://www.growup.org.uk/) producing salads, herbs and tilapia, Yep Yep Farm, Dexter, Oregon growing lettuce, greens, herbs and tilapia (http://www.yepyeporganicfarm.com/), cannabis producer Green Relief, Canada (https://www.greenrelief.ca/). Tsar Nicoulai, California, USA harvest caviar along with lettuce (https://tsarnicoulai.com/) and Tailor Made Fish Farms, Australia produces fresh Barramundi dish and Leafy Vegetables (https://www.tailormadefishfarms.com.au/). Community involved urban aquaponics examples include Farm on Ogden in Lawndale neighborhood of Chicago growing lettuce and tilapia.

Indoor urban agriculture is growing

Indoor urban agriculture i.e., CEA in urban settings, is bringing fresh produce farms closer to cities where consumers live. The popularity of indoor urban agriculture is increasing due to its many advantages such as fresher food, the capacity to grow crops irrespective of weather, less spoilage due to shorter transit distances, and small transportation carbon footprint (Lempert, 2018; Marston, 2018; Meharg, 2016). Globally, urban agriculture involves over 100 million people and contributes to global food security by providing high yield fresh vegetables per unit area (up to 50 kg per m^2 or more per year) (Eigenbrod & Gruda, 2015). In the US, many large cities such as New York City, Chicago, Detroit, and Boston are providing support to indoor farming projects, which are very successful. For example, Farm on Ogden in the Lawndale neighborhood of Chicago has a facility with a 7,300 square feet greenhouse, which grows seasonal vegetables year-round. The facility has a 50,000-gallon aquaponics system that produces 2,500 heads of lettuce every week, year-round, and 14,000 pounds of tilapia a year (Marston, 2018) (Figure 1). Lufa Farms in Montreal, Canada is also an example of a large commercial hydroponic farm using use vacant roof spaces. They have recently built one of the largest rooftop farm of 163,800 square feet greenhouse that is water and energy efficient. (https://montreal.lufa.com/en/about).

Figure 1. The Farm on Ogden in Lawndale neighborhood of Chicago, supports and sustains a healthy urban community by bringing food, health, and jobs together in one location (Marston, 2018). (Source: https://www.chicagobotanic.org/urbanagriculture/farm_on_ogden)

Vertical model of urban agriculture

The vertical farming model of urban agriculture produces crops in racks stacked vertically. It helps to increase crop production per unit area as crops are grown in multiple layers. Vertical farming can utilize abandoned warehouses and buildings as well as shipping containers for growing the crops. Container vertical farms use 40-foot long recycled shipping containers to build self-contained units with computer-controlled growth management systems for a variety of plants (Birkby, 2016). Only a few commercial-scale vertical farms existed until early 2015, but recently an increasing number of farmers have shown interest in commercial vertical farms (Birkby, 2016). In the US, vertical farming is expected to increase at a compound annual growth rate (CAGR) of more than 24% between 2018-2022 and reach values of about $3 billion (Lebkanc, 2019).

Some successful examples of vertical farms include aeroponics based AeroFarms, Newark (Figure 2), New Jersey that produces baby greens and microgreens (http://aerofarms.com); shipping container-based CropBox, Clinton, North Carolina that grows greens, lettuce, herbs, strawberries, microgreens and fodder (www.cropbox.co); hydroponic vertical farm Local Garden, Vancouver, British Columbia, Canada that grows leafy greens, microgreens, and strawberries (www.localgarden.com); and Intelligent Growth Solutions Ltd (IGS), Scotland that uses indoor vertical growth facilities based on efficient internet-enabled smart lighting with automation and power management (https://www.intelligentgrowthsolutions.com/).

World's largest vertical farming facility is being built by Crop One Holdings in Dubai, United Arab Emirates. This controlled environment vertical farm will have 130,000 square feet coverage with daily production of 6000 pounds of high quality, herbicide and pesticide free leafy greens (http://croponeholdings.com/news/page/2/). French startup Agricool uses containers with controlled temperature, humidity, CO2 level, color spectrum and day/night cycle to grow fruits and vegetables in urban areas, at three locations in France and one in Dubai (https://www.agricool.co/en/). Belgium based Urban Crop Solutions helps build fully automated vertical farms using LED lighting for more than 200 crop varieties (https://urbancropsolutions.com/). Jones Food Company Ltd. (UK and the Netherlands) has built approximately 54,000 square feet, one of the largest hydroponics based vertical farm in Europe, producing up to 420 tons of leafy greens per year (https://www.jonesfoodcompany.co.uk/). In South Korea, world's first tunnel based vertical farming grows leafy greens and strawberries on 71,000 square feet (http://www.inexton.com/index.php).

Figure 2. Vertical farm by AeroFarms, Newark, New Jersey (Source: https://aerofarms.com/)

Indoor farming and the promise of food safety

The number of foodborne outbreaks related to fresh produce has increased significantly in recent years. In the US, between the years 2004 and 2013, fresh produce was linked to foodborne outbreaks causing more than 21,000 illnesses from more than 630 outbreaks (Center for Science in the Public Interest (CSPI), 2015). According to the report from the CSPI, for most of the outbreaks, the point-of-contamination of pathogens occurred earlier in the distribution chain, i.e., on a farm or at a distribution center. Controlling contamination in open farms is difficult due to the possibility of unpredictable and uncontrollable events such as wind, dust, birds, wild animals, etc. Indoor farming, on the other hand, provides an opportunity to mitigate the risk of pathogen contamination and can improve traceability. Indoor farming offers a cleaner production environment for growing fresh produce that are more likely to be consumed raw without a kill step involved.

Although contamination through the environment is better controlled in indoor farming, indoor farming is not immune to pathogen contamination. In addition, any contamination introduced through humans, irrigation water, or nutrient source can get multiplied indoors and is difficult to control as water and air are circulated inside the farm. Indoor growers are realizing the importance of food safety for the crops grown indoors. They are taking measures such as the use of good manufacturing practices including use of hairnet, face masks, sanitizing foot bath, use of single-use clean cloths, etc. (Cosgrove, 2018). The growers are also following the standards for food safety by keeping records of frequent audits or certifications such as Global Food Safety Initiative's (GFSI) Food Safety Management System, Global Good Agricultural Practices (GAP), Canada GAP, Hazard Analysis Critical Control Points (HACCP), and Safe Quality Food (SQF) Programs (Cosgrove, 2018). A new policy by the USFDA- Food Safety Modernization Act (FSMA) for farms with annual sales of over $500,000 requires routine inspections to prevent food-borne outbreaks on the farms (Cosgrove, 2018). Some growers including BrightFarms (NewYork, NY), AeroFarms (Newark, New Jersey), Little Leaf Farms (Shirley, MA), Revol Greens (Medford, MN), Plenty (San Francisco, CA), and Bowery Farming (NewYork, NY) have established a food safety coalition for CEA growers in order to protect consumers by setting standards and sharing insights (Flynn, 2018). These measures will help indoor farmers establish protocols and standards for microbial safety of fresh produce grown in CEA.

Indoor farming is getting data-driven and tech-obsessed

For increasing the production efficiency, indoor farmers are using automation and machine learning for operation from seeding to harvesting (Kuhn, 2019). The cost of labor is one of the major reasons for using automation in indoor farming (Kuhn, 2019). Sensors are being used for collecting data on plant growth, air flow, light, water, and humidity in the controlled environment. Process controls are performed based on collected data to maximize the growth by supplying the correct amount of light, air, water, plant nutrients, and indoor environment conditions using computer-assisted control systems (Despommier, 2017). Machine learning and artificial intelligence (AI) are being used to analyze the data for optimum use of resources such as water and nutrients (Kuhn, 2019).

A California based Start-up Iron Ox uses robots for planting, caring, and harvesting produce in an indoor hydroponic farm (Figure 3). Hydroponic growth modules with different spacing are used during three different stages of growing and a robotic arm is used to move the plants from one module to another (Vincent, 2019). The company also uses machine learning and AI for detecting pests, diseases, and defects by using 2D and 3D images of plants and neural network modeling to compare with healthy produce (Brigham, 2018). Based on detected pest and diseases, appropriate remedies are provided, for example, the infected plants are removed before pest start spreading (Brigham, 2018) to healthy plants.

Figure 3. Iron Ox uses Robot arms in indoor farming (Source: http://ironox.com/)

AeroFarms from New Jersey with collaboration with Dell Technologies uses automation and data analytics for its indoor farming operations from seed to package. It uses technology for smart use of nutrients, water, oxygen, and LED lights with 130,000 data points for every harvest (https://aerofarms.com/technology/). It utilizes reusable BPA-free, post-consumer recycled plastic medium for growth, smart pest management practices, and customizable building blocks modules for achieving high yield per square foot.

France based Myfood uses smart box to collect parameters such as acidity and the temperature of the water to generate a real knowledge base. They use neuromimic algorithms to extrapolate behaviors and provide real support. The models are constantly refined to allow a better management of the greenhouses (https://myfood.eu/our-technology/iot-artificial-intelligence/). US based Infinite Acres is a tech company (https://infinite-acres.com/) that supports the growers in robots and automation, lighting, sensors, and vision systems.

Future of indoor farming: advances of sustainable plasma technology to improve plant yield, food safety, and quality

Indoor farming is alleviating some of the pressure on the environment by efficient use of natural resources to grow fresh produce. The sustainability of indoor farming methods can be further improved by using chemical residue-free fertilizers and sanitizers. Cold plasma is one such a technology which does not leave any chemical residue and can be used to generate on-demand nitrogen fertilizer and sanitizers.

Plasma, the fourth state of matter, is a partially ionized gas consisting of charged species, excited atoms and molecules, and high energy photons. Cold atmospheric pressure plasma (CAP) is generated at atmospheric pressure, usually from air. Exposing water and water microdroplets to CAP from air, leads to formation of plasma-activated water (PAW) and plasma-activated mist (PAM), respectively. PAW and PAM contain reactive nitrogen and reactive oxygen species including nitrogen oxides (NO_x), mostly nitrite

(NO_2) and nitrate (NO_3) and their corresponding acids, hydrogen peroxide (H_2O_2), and ozone (O_3) (Scholtz et al., 2015). CAP, PAW, and PAM have been shown to exhibit antimicrobial and antifungal properties (Bourke et al., 2018). PAW and PAM are more environmentally friendly compared to traditional chlorine and ammonia-based chemicals because the chemically reactive species in PAW and PAM slowly degrade to natural compounds over time. PAW and PAM can be prepared on location and on-demand, reducing the costs and risks associated with transportation and storage of chemicals currently used in chemical sanitation processes. Additionally, active antimicrobial compounds in PAW and PAM are not associated with the formation of carcinogenic halogenated by-products, such as trihalomethanes (THMs) and haloacetic acids (HAAs) associated with chlorine-based sanitizers (Ölmez and Kretzschmar, 2009). Like other sanitizers, PAW and PAM are effective as a surface treatment. However, PAW and PAM are less detrimental to the quality of food and to the environment but are effective for pathogen inactivation.

PAW has also been used as a fertigation technique to improve plant germination rates and seedling growth (Bourke, Ziuzina, Boehm, Cullen, & Keener, 2018). CAP and PAW have been used to degrade pesticides, control pests, remove mycotoxins and improve physiological quality, germination, growth, vigor, fresh weight, overall yield, and shelf-life of the crops (Bourke et al., 2018). Previous studies have shown beneficial effects on the germination of seeds by applications of cold plasma directly (Filatova et al., 2016; Jiafeng et al., 2014; Junkar, et al., 2016; Volin, Denes, Young, & Park, 2000). Recent studies showed applications of PAW in plant growth for better yield and nutrition in association with reduced water consumption (Brar, et al., 2016; Lindsay et al., 2014; Park et al., 2013; Peethambaran et al., 2015; Sarinont et al., 2017; Sivachandiran & Khacef, 2017). Positive effects on seed germination of mung beans and increased growth (by 60% as compared to control) of tomato and pepper plants were demonstrated from CAP treatment of seeds and by PAW-15 (15 min plasma treatment) irrigation for 9 days (followed by 51 days tap water) (Sivachandiran & Khacef, 2017). Similar or increased plant weight and length were observed for alfalfa, pole beans, watermelon, and zinnia (Park et al., 2013) using PAW. Sarinont et al. (2017) observed that long-living reactive oxygen species (ROS) and reactive nitrogen species (RNS) in PAW were the key factors for plant growth.

Application of plasma-bubbling in hydroponic culture has been shown to result in significant reductions (up to 6 log CFU/ml) of E. coli, E. faecalis, P. aeruginosa, and S. aureus (Kawano et al., 2016). PAW has been shown to exert anti-microbial effects against many microorganisms in fresh produce (Guo et al., 2017; Jiang et al., 2017; Joshi, et al., 2018; Kamgang-Youbi et al., 2008; Kamgang-Youbi et al., 2009; Ma et al., 2015, 2016; Rodrigues et al., 2017). Overall, CAP based technology has the potential to be used for different applications at various stages of crop production especially in indoor agriculture. CAP being metastable, chemical residue-free, and at low (near room) temperature, makes it a sustainable technology that does not damage crops, food, seeds, environment, and humans (Ohta, 2016). Herein we will discuss a few case studies on the use of CAP in indoor agriculture.

Plasma treatment of water is being seen as an alternative nitrogen fixation method. As opposed to energy and fossil-fuel intensive chemical Haber-Bosch process used in the industry, plasma-based nitrogen fixation method mimics nature (Lindsay et al., 2014). In nature, lightning, a form of plasma, induces dissociation and reaction between atmospheric nitrogen and oxygen to fix atmospheric nitrogen (Lindsay et al., 2014). Lindsay et al. (2014) designed a low-voltage large volume glow discharge to treat water to generate PAW. PAW fertigated radishes, marigolds, and tomatoes in soil-based system showed that shoot masses grew 1.7- 2.2 times longer than water irrigated controls. Though PAW treated plants had higher average plant height, it was not statistically different from control. The average plant weight of PAW irrigated plants was significantly higher than control.

In a study by Brar et al. (2016), A. thaliana plants (mouse-ear cress) were irrigated with plasma-activated water with simulated drought conditions. It was found that PAW irrigated A. thaliana plants showed higher tolerance for drought, based on the changes in their physiology in certain stress-related genes. Plants also showed increased growth, suggesting PAW as an alternative option for improving the growth of plants, and for reducing fertilizer and soil treatment.

Zhang et al. (2017) used plasma-treated tap water, demineralized water, and liquid fertilizer and studied their effects on germination rate and stem elongation rate on lentils. Plasma-treated tap water resulted in the germination rates of 80% compared to 30% with just tap water. Higher stem elongation rates and final stem lengths were obtained using plasma-treated tap water compared with commercial fertilizer. On the contrary, plasma treatment of demineralized water reduced the germination rate to 54% compared to 71% from untreated demineralized water. The difference might have been due to less nitrate concentration in plasma-treated demineralized water (50 µM) compared to the tap water (470 µM). The study also suggested that plasma-generated species in the plasma-activated tap water can auto-degrade in a few hours as opposed to liquid fertilizer which can induce long-term harmful pollution.

Okumura et al. (2016) developed a plasma treatment for 15 L liquid fertilizer (nutrient solution) in a tomato hydroponic growing system. The hydroponic system was inoculated with a plant pathogen R. solanacearum. Control plants did not survive due to the bacterial infection while plants from plasma-treated liquid fertilizer grew healthy. Control plants showed 100% disease severity compared to 20% plasma-treated liquid fertilizer grown seedlings. Plasma treatment was able to reduce levels of plant pathogens R. solanacearum by 5 CFU/mL. Similar reductions in R. solanacearum (4 logs) were observed by Takahashi et al. (2018) during the plasma treatment of inoculated liquid fertilizer.

In a study published in the Scientific Reports by Nature, Lee et al. (2018) explained the roles of oxides of nitrogen in plasma activated water on quality enhancement of soybean sprouts. Plasma treatment was used to recycle water during the hydroponic production of sprouts. It resulted in a reduction of overall aerobic microbe count by 4.3 log CFU/ml and by 7.0 log CFU/ml of inoculated S. Typhimurium, within 5 minutes and 2 minutes, respectively. Oxides of nitrogen in PAW enhanced sprout growth, hypocotyl elongation, and asparagine accumulation. Reactive oxygen species and NOx in PAW improved ascorbate and γ-aminobutyric acid (GABA) accumulation in the hypocotyls and radicles of the soybean sprouts. The study suggested that cold plasma technology can be an economical option to produce nutritionally rich and microbiologically safer soybean sprouts in a shorter period of time. They also suggested that research is needed to optimize the concentration of plasma-discharged species in irrigation water and to understand the mechanism of nutrition accumulation.

Together, these studies provide enough evidence on a smaller scale to suggest that cold plasma to be a viable option for sanitation, fertigation, and water recycling treatment that can result in an increased microbiological safety, improved/comparable plant growth, and better quality. The technology has the potential to be extended to larger-scale systems to create a safer and sustainable growth environment for improved quality, nutritious, chemical residue-free, and microbiologically safer produce while providing a higher yield.

The use of plasma-activated water/mist (PAW/PAM) in agriculture for crop cultivation is a novel but a largely untapped area. PAW, if combined with indoor agriculture, has the potential to increase yield and plant growth by using fewer natural resources such as water and land. However, successful and safe scale-up of the technology to a commercial greenhouse level scale is yet to be demonstrated and needs further research & development. CAP based technologies are at the advanced development stage with technology readiness level (TRL) of 5, for which further research and development are essential to design systems that are scalable to industrial requirements (Hertwig et al., 2018). In addition, the economics of the process has not been fully investigated. More investigations on worker safety during plasma equipment operations in terms of high voltage and emission of ozone or NO_X are needed. There are currently no regulations from any US or non-US regulatory agencies, regarding plasma-based nitrogen fertilizers. Finally, although CAP, PAW, and PAM are chemical input-free, whether these technologies may receive acceptance in organic farming is not clear (Niemira, 2012).

Conclusions

There is an increasing interest in soil-less indoor farming methods such as vertical farming and urban farming using hydroponics or aeroponics. These farmers are looking for ways to sustainably improve the yield using minimal natural resources without compromising food safety and quality. Indoor farming community is using high-end technology for automation and data mining to improve productivity. The indoor farms have improved standards for food safety. New technologies based on cold atmospheric pressure plasma have shown the potential for higher growth and improved microbiological safety which can be attained sustainably in controlled environment agriculture or indoor farming. Scale-up, regulatory approval, and economics of the plasma process, and acceptance by consumers still need to be addressed for successful commercialization.

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The International Union of Food Science and Technology (IUFoST) is the global scientific organization representing more than 300,000 food scientists and technologists from its work in over 100 countries around the world. IUFoST is a full scientific member of ISC (International Science Council) and the only elected global representative of Food Science and Technology in the ISC. IUFoST represents food science and technology to international organizations such as WHO, FAO, UNDP, UNIDO, The World Bank, and others. IUFoST organizes world food congresses, among many other activities, to stimulate the ongoing exchange of knowledge and to develop strategies in those scientific disciplines and technologies relating to the expansion, improvement, distribution and conservation of the world's food supply.

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