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The Transformative Environmental Effects Large-Scale Indoor Farming May Have On Air, Water, and Soil

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ABSTRACT: This article identifies the potential environmental effects large-scale indoor farming may have on air, water, and soil. We begin with an overview of what indoor farming is with a focus on greenhouses and indoor vertical farms (eg, plant factories). Next, the differences between these 2 primary methods of indoor farming are presented based on their structural requirements, methods of growing, media, nutrient sources, lighting requirements, facility capacity, and methods of climate control. We also highlight the benefits and challenges facing indoor farming. In the next section, an overview of research and the knowledge domain of indoor and vertical farming is provided. Various authors and topics for research are highlighted. In the next section, the transformative environmental effects that indoor farming may have on air, soil, and water are discussed. This article closes with suggestions for additional research on indoor farming and its influence on the environment.

KEYWORDS: Indoor farming, vertical farming, vfarm, zfarm, plant factory, water, air, soil, sustainability, carbon cycles, drought, information technology, greenhouse gases, climate change, environment, agtech

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Introduction

Open field farming has been practiced the same way for centuries as the primary means of growing food. Its origins can be traced back to wheat production 11 000 years ago in the Middle East, which later spread to the Mediterranean, north-Africa, and elsewhere.[1] Given limitations on the amount of arable land, water scarcity, increased awareness of sustainable development, and the well-documented environmental effects of open field agriculture, other farming methods have been developed in the past few decades. The primary alternative to open field farming is referred to as indoor farming, which has received relatively little attention in terms of environmental impacts. The goal of this article is to introduce indoor farming in its many forms to environmental scientists, outline key areas of research, and highlight the effects large-scale indoor farming could have on the environment. Research needs to be done to better understand the cumulative and transformative environmental effects indoor farming methods may have on water, air, and soil as it realizes its potential to supply a significant portion of the population with fresh food.

What Is Indoor Farming?

Indoor farming is a relatively new method of growing vegetables and other plants under controlled environmental conditions. These farm systems are variously referred to as indoor farms, vertical farms, vfarms, zfarms, greenhouses, controlled environment agriculture (CEA), and plant factories.[2,3] Indoor farms are sometimes confused with urban farms, which typically represent small outdoor farms or gardens to grow vegetables that are located in urban areas. It also should be noted that mushrooms have been grown indoors in compost under controlled conditions without light for more than one hundred years.[4] For the purposes of this article, we will focus on characteristics of controlled environment indoor vertical farms and greenhouses, which are the primary architectures used for the large-scale production of leafy greens and other vegetables that require natural or artificial light.

The many faces of indoor farming

Greenhouses have been the workhorse for indoor growers for decades, especially in the production of flowers and ornamental plants. The modern high-tech greenhouse designs were pioneered in the Netherlands and have since been embraced all over the world. Several examples of these farms are evident throughout the United States and the largest span hundreds of acres. For example, according to Greenhouse Grower,[5] Altman Plants (CA) has almost 600 acres under glass followed by Costa Farms (FL) with 345 acres. These are mainly used in the production of ornamental plants.

For vegetables, greenhouses were originally designed for tomatoes, but now are used in the production of kale, microgreens, lettuces, herbs, squash, and other types of fresh produce. These greenhouses, formerly located in rural areas, are now being positioned near urban and peri-urban areas to bring operations closer to population centers to save money and reduce the carbon footprint associated with transportation miles. For example, BrightFarms (brightfarms.com) has greenhouse operations located just outside of Philadelphia and Cincinnati to produce lettuces and other leafy greens. Gotham Greens (gothamgreens.com) situated its first greenhouse on top of a warehouse in Brooklyn, NY and has since expanded to other cities. AppHarvest (appharvest.com) is a venture located in Kentucky whose greenhouses cover more than 60 acres to produce tomatoes and other vegetables. What is common to greenhouse design is that all growing takes place on a single level, they are clothed in materials such as glass that transmit natural sunlight, and include climate control and irrigation equipment. They may also use a modest amount of supplemental artificial lighting during winter months.[6]

Growing leafy greens and other plants in buildings has emerged in the past 25 years whereby plants are grown vertically and hydroponically using artificial lights. Indoor vertical farms are typically located in warehouses or similar structures that have been retrofitted to provide superior heating, ventilation, and cooling (HVAC) for the benefit of plant production and racking systems to support the production systems.[7-9] The PVC grow systems transport nutrient-rich water to the root zone of the plants, and the water is then returned to the main reservoir. Designed as closed re-circulating systems, indoor vertical farms only use a fraction of the amount of water as greenhouses or open-field methods (see also section "Water Use"). The advent of cost-effective LED lighting technologies has allowed farmers to provide the plants with just the right wavelengths of light, intensity, and photo-period to optimize growth.[10] Other advances include automation, IoT, and artificial intelligence; ie, all of the information technologies that contribute to "smart farming."[11]

Although modern LEDs are very efficient compared to HID, high-pressure sodium or florescent lamps, the capital and operating costs of these artificial lighting systems are significant,[10] as are the climate control systems that are also required. Greenhouses, for example, require significant investment in heating and cooling equipment to maintain stable temperatures and humidity, which result in significant operating costs in buildings with low R-value membranes (eg, glass). The chief benefit of this design is that the light comes free, although growing is limited to a single level. Indoor vertical farms, however, can benefit from well-insulated structures that reduce heating and cooling costs and growing can take place on multiple levels. That said, these savings come at the expense of relatively high electricity usage for artificial lighting.[10] These operating costs can be mitigated with the increasing efficiencies of LED's, sensing systems that modulate light to the maximum required for the plants, pairing indoor farms with renewable energy sources such as solar and geo-thermal, and architectures that favor energy efficiency.[9]

Methods of indoor farms

Indoor farms are characterized by several parameters:

- Growing Method and Media
- Source of Nutrients
- Lighting Requirements
- Facility Capacity
- Climate Control
- Economics

Most indoor farms use hydroponic methods of growing; ie, plants are grown in water. Seeding takes place in an inert material such as stone-wool or peat, which is irrigated with nutrient–rich water. Water is administered using a variety of techniques ranging from fine mist sprayers (aeroponics), to shallow water (NFT) irrigation, to deep water culture (DWC) immersion to flood and drain methods.[9] All are effective and have their pros and cons. Nutrients for larger scale hydroponic production systems typically come from dissolved salts that ionize in the water. In some smaller systems, the nutrients come from the nutrient-rich water of fish farms (ie, aquaponic systems) that are proximate to and coupled with the plant production system.[9]

In greenhouse production facilities, most lighting comes from the sun, which may be supplemented with artificial light, especially in the northern latitudes during winter. Plant factories and vertical farms, however, use only artificial lighting but are designed to maximize growing area using stacking methods. One common design is characterized by horizontal multi-tier growing systems starting at ground level that may include up to a dozen growing levels or tiers. Aerofarms (aerofarms.com) and Bowery Farms (boweryfarming.com) use this type of design for their production processes. An alternative is to use vertical drip irrigation grow systems. This design is characterized by vertical multi-site growing systems starting at ground level that extend upwards of 8 ft. In these systems, plants grow "sideways" toward artificial lights that are positioned at a right angle. Plenty, Inc. (plenty.ag) uses systems like these obtained in the acquisition of Bright Agrotech. Several examples of vertical farming ventures can also be found in Al-Kodmany.[9]

All indoor farming methods share the characteristic of offering CEA. Controlled environment agriculture offers the grower complete control over several environmental variables including, but not limited to: light intensity and wavelength, photo-period, wind velocity, temperature, and humidity. Water culture is further managed to obtain optimal results based on nutrient levels, PH, and dissolved oxygen.[9,12] In most cases, pesticides and herbicides are eliminated. More advanced farms such as Fifth Season (fifthseasonfresh.com) benefit from extensive use of sensors, IoT, robotics, automation, and control systems designed to optimize yields and minimize labor. Another valuable aspect of CEA farms is their ability to produce plants with certain desired morphologies and nutritional profiles based on the control of lighting wavelength, temperature, and nutrient levels. SharathKumar et al[13] go so far as to suggest that with CEA, we are moving from genetic to environmental modification of plants.

Benefits and challenges of indoor vertical farms

Several benefits are associated with vertical farming,[9] although the industry is not without its challenges (see Table 1). The

Table 1. Benefits and challenges of indoor and vertical farming.

BENEFITS	CHALLENGES
No or reduced pesticides	Still only a small % of U.S. food production
Uses much less water	Need to demonstrate scale
Prevents fertilizer run-off into eco-system	Indoor farming not tracked by USDA
Most yields per ft^2	Limited number of cultivars can be grown profitably indoors
Price stability	High capital start-up costs
Premium pricing	Profitability elusive
Reduced labor possible	Prices of produce still higher than conventional
May be located closer to urban centers	Vertical farms require significant energy
Resilient to climate change, drought, etc.	Industry still seeking metrics and standards

Abbreviation: USDA, U.S. Department of Agriculture.

principal sustainable benefits of indoor vertical farming are a large reduction in the use of water (see also section "Water Use"), the reduction or elimination of pesticides, and mitigation of the effects of excess fertilizer run-off. From an economic perspective, the ability to control the environment results in a stable supply chain, price stability, long-term contracts with distributors and retail markets, and high yields per square foot. The elimination of pesticides puts produce grown this way on par with organics, which command premium pricing. Indoor farms, if designed correctly, can reduce labor costs and may be located closer to urban centers. Some see a role for indoor farms to ameliorate food deserts, unemployment, and as a means to re-purpose abandoned buildings and lots.[3,9,14-16] Finally, vertical farms provide resilience to climate change, flooding, droughts, etc.

However, the vertical farming industry is facing some key challenges. For instance, currently only a very small portion of fresh vegetables are produced indoors. The one exception is the mushroom industry, which represents a US$1.15 billion industry.[17] Second, the USDA does not clearly identify vegetable production by method; eg, greenhouse, open field, vertical farm, etc, so data are not readily available. Third, profits have been elusive, especially for vertical farms.[18] According to the 2019 Global CEA Census Report only 15% of shipping container farms and 37% of indoor vertical vertical farms were profitable vs. 45% for greenhouse operations.[19] Another limitation of indoor farming is that a relatively small number of cultivars can be grown using indoor farming methods. The primary ones are leafy greens, herbs, microgreens, tomatoes, and peppers, although berries, root vegetables and other more exotic plants are being trialed.[19] Another challenge for indoor farm start-ups are the high capital costs, which can range from US\$50-150/ft^2 for greenhouses to US\$150-400/ft^2 for vertical farms. For example, AppHarvest had to raise over US$150 million to fund its 60 acre greenhouse complex.[20] Aerofarms raised US\$42 million for a 150 000 ft^2 vertical farm,[21] which equates to over US\$280/ft^2. Cosgrove[22] further reports that access to capital is impeding the growth of indoor farming, especially for smaller farms. One reason that indoor vertical farms are not easily profitable is that they have to compete against conventional farms, which still enjoy a cost advantage. As a result, indoor farms typically price product toward the high end and along the lines of pricing for organics,[2] which limits market penetration. The 2 major factors contributing to the high costs of indoor and vertical farm operations are energy[10,23,24] and labor, which account for nearly 3 quarters of the total.[2,24] Despite these challenges, venture capital continues to pour money into indoor farming and agtech in the hopes of driving cost down and maintaining growth. Dehlinger[25] reported that US$2.8 billion was invested by venture capitalists in Agtech companies in 2019.

Finally, the industry is struggling to share knowledge, establish standards, and create best practices, although progress is being made. For example, the Center of Excellence for Indoor Agriculture established a "Best in Class" award for growers and manufacturers (indoorgacenter.org). Indoor Ag-Con (indoor.ag) and the Indoor Agtech Innovation Summit (rethinkevents.com) hold online events and annual conferences to help promote knowledge sharing. Several specialized industry news outlets now exist including Vertical Farm Daily (verticalfarmdaily.com), Urban Ag News (urbanagnews.com), iGrow (igrow.news), Hortidaily (hortidaily.com), AgFunder Network (agfundernews.com), and others.

Research on indoor farming

Research on indoor farming and vertical farming has been ongoing for several years and represents multiple topics and streams. A map produced by VOSviewer[26] of the research landscape of ideas based on the co-occurrence of keywords (eg, "vertical farming"; "indoor farming") appearing in Scopus is

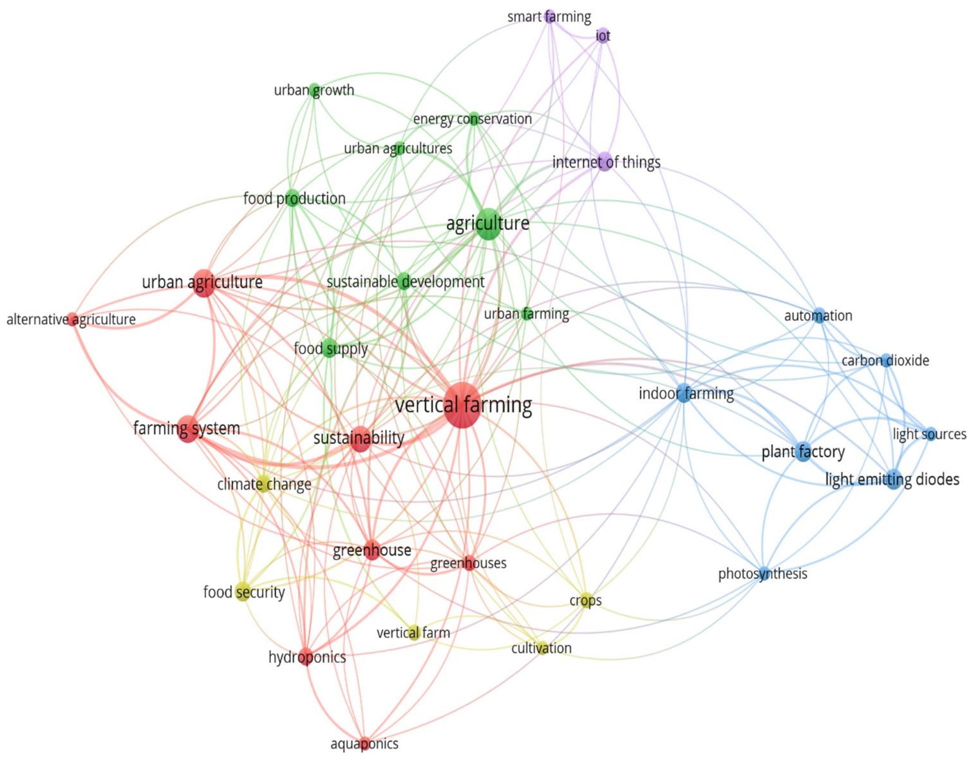

Figure 1. Map of research and knowledge domain of indoor farming.

illustrated in Figure 1. Four clusters of research are represented in the map: (1) Vertical Farming (red), (2) Plant Factory and Indoor Farming (blue), (3) Agriculture and Urban Farming (green), and (4) Smart Farming (purple).

Research on indoor farming includes farm production capabilities,[12] profitability and economics,[18,27] pest and disease management,[28] building information modeling,[29] energy management,[23,30] sustainability, urban planning and food security,[3,9,14-16] plant science,[13] and smart farming.[11] An excellent source of knowledge on indoor farming and plant factories can be found in Kozai et al.[8,9] Topics include the impact of indoor farms on urban areas, global case studies, energy and resource use, operating efficiencies, plant science, systems design, growing methods and materials, indoor production processes, measurement, automation, sustainability of indoor farms, and next-generation designs.

Potential Effects of Indoor Farms on the Environment

Water use

Water scarcity is a significant problem in many parts of the world.[31] One of the most frequently touted benefits of indoor farming is the reduced use of water. For example, many indoor re-circulating vertical farms quote a 90%-95% reduction of water usage vs open-field farming. Let's examine those claims in the context of lettuce production. An early estimate by Hoekstra[32] indicated that lettuce grown in an open-field setting required a global average of 130 L of freshwater per kilogram. A more recent study by Barbosa et al[33] found that conventional lettuce grown in southwestern Arizona required 250 ± 25 L/kg vs 20 ± 3.8 L/kg for lettuce grown hydroponically; ie, only about 8%.

Another study by Chance et al[14] analyzed the inputs and outputs of a small indoor vertical farm in Chicago using Material Flow Analysis (MFA). Inputs included water, raw materials (eg, seed, nutrients, rock-wool), cleaning fluids, and energy (eg, electric). Outputs included the product (eg, lettuce and microgreens), solid waste (plastic, burlap and rock-wool), and wastewater. According to the study, the system only used 30 gallons of water (113.5 L) to produce 41 pounds of lettuce and microgreens (18.5 kg), which translates to 6.14 L/kg of water use for lettuces and microgreens. Water usage in this indoor farm thus amounted to only 2.4%-4.8% of that required to grow lettuce using open field methods, thus lending credence to claims being made by many indoor farmers.

A similar conclusion using a more robust framework based on resource use efficiency (RUE) was demonstrated by Kozai[34] and Kozai and Niu.[35] According to the data provided by several researchers and their models, indoor farms designed as "plant factories" consume water with 0.95-0.98 water utilization efficiencies (WUE) vs 0.02-0.03 efficiencies for greenhouses. These results suggest that water use reductions of this magnitude could have significant effects should indoor farming expand on a massive scale globally.

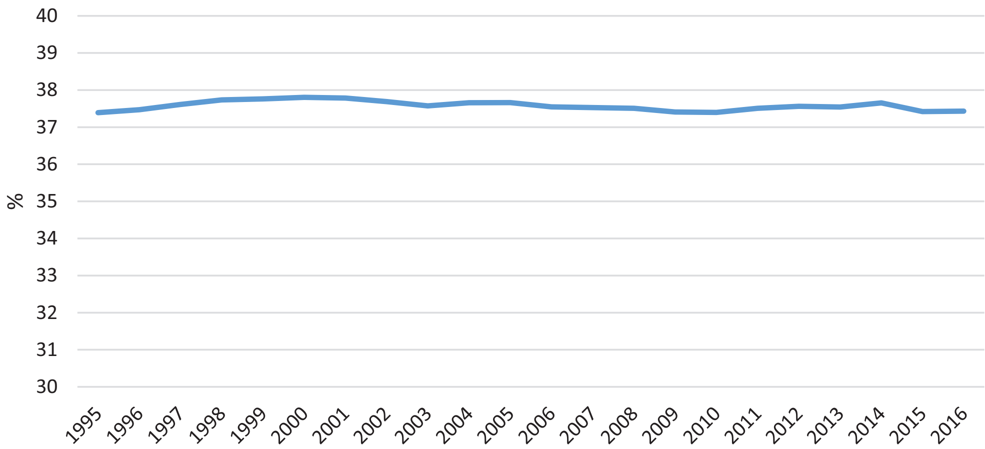

Figure 2. Agricultural land as a percentage of total land area.
Source: World Bank.[51]

Water run-off

If is well-known that agriculture contributes to nutrient loading of freshwater bodies,[36,37] from coastal aquifers[38] to lakes[39] to bays such as the Chesapeake[40-42] to rivers through subsurface drainage.[43] According to the U.S. EPA,[44] high levels of nitrogen and phosphorus can cause eutrophication of water bodies, which can lead to hypoxia, causing fish kills and a decrease in aquatic life. Furthermore, excess nutrients can cause harmful algal blooms that not only disrupt wildlife but can also produce toxins harmful to humans. The EPA observes that not only does nitrogen loss affect waterways but also affects air quality and climate change with the release of gaseous nitrogen-based compounds (see also section "Effects on soil"). Improved land use and management techniques are found to improve these outcomes. Indoor farming also can help avoid these externalities.

Another benefit of indoor farming is that little or no pesticides are used to control pests. Open-field agriculture practices in comparison can lead to contamination of groundwater, rivers, lakes, and coastal waters by pesticides and herbicides[45-47] as well as have toxic effects on human health and other organisms (eg, birds, fish, beneficial insects); decrease the quality of food commodities; contaminate soil; and decrease soil fertility as well as affect air quality.[48,49]

Effects on soil

Most indoor farming is soilless; ie, crops are grown without soil by seeding in inert materials such as stone-wool or peat and submerging the latter in water. Thus, the principal benefit of indoor farming regarding the land is the fact that no soil is used. This approach to food production has several positive consequences for land use and the environment.

Soil consumption

Indoor farming reduces the pressure to cultivate what little land is available for agriculture. According to the World Bank[50] and the FAO, about 11% (1.5 billion ha) of the globe's land surface (13.4 billion ha) is arable (Arable land includes land defined by the FAO as land under temporary crops [double-cropped areas are counted once], temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded[50]). This percentage has remained nearly unchanged for half a century ranging from 9.8% in 1961 to 11% as of 2016. Thus, without dramatic changes in the earth's land mass, the potential to expand the use of existing arable land for agriculture is thereby limited.[12] This conclusion is confirmed by recent data showing agricultural land (agricultural land refers to the share of land area that is arable, under permanent crops, and under permanent pastures[51]) as a % of total land area.[51] Agricultural use as a percentage of total land area has only varied slightly from 37.39% in 1995 to 37.80% in 2000 to 37.43% in 2016 (see Figure 2). Indoor farming thus decreases pressure to convert idle arable land to agricultural use.

Soil erosion and biodiversity

Another significant externality avoided with indoor farming methods is the adverse effect open-field agriculture can have on soil texture, biodiversity, and erosion.[52] Tsiafouli et al[53] determined that increasing levels of farming intensity reduce soil bio-diversity, which can threaten agricultural production itself. It is well known that sub-optimal farming methods, animal grazing, and native forest removal can greatly accelerate soil erosion.[1,54] Montgomery[55] found that conventionally plowed fields averaged 1-2 orders of magnitude greater erosion than under native or perennial vegetation. Modern land management and conservation methods can mitigate many of these effects if implemented correctly and on a wide-scale basis.[56]

Agricultural soil as carbon sinks

Many agricultural practices deplete the soil of carbon, thus adding to CO_2 emissions. Tillage in particular can contribute significantly to carbon dioxide emissions.[57] Indoor farming provides the opportunity to reduce tillage and transition agricultural soils and arable lands back to forest or perennial species. By doing so, the capacity for carbon sequestration increases. Paustian et al.[58] suggest that soil management methods can have an impact of 3%-6% of total fossil C emissions. They further suggest that such strategies can also improve agricultural productivity and sustainability.

Effects on air

In the United States, agriculture accounts for about 10% of greenhouse gas (GHG) based on 2018 data.[59] The most recent Intergovernmental Panel on Climate Change report[60] estimates that globally about 24% of all GHG emissions come from agriculture and related uses.[61] Opportunities to move from open field farming to indoor farming could potentially have significant impacts on air quality and the production of GHGs, especially through the conversion of open-field agriculture to forest. For example, Waheed et al[62] modeled data from 1990 to 2014 and found that CO_2 emissions can be reduced by increasing renewable energy usage and forest area, while decreasing agricultural use. Furthermore, food production using open-field agricultural methods accounts for nearly 70% global atmospheric input of nitrous oxide (N_2O) and 40%-45% of global atmospheric input of methane (CH_4).[63-65] This issue is particularly evident in the United States with the extensive application of nitrogen-enhancing products to open fields in the form of fertilizers, manure, and legumes.[66,67] In addition to migrating to waterways and groundwater, the excess nitrogen is liberated into the atmosphere, resulting in the production of nitrous oxide and nitrogen oxides. Various strategies are recommended to mitigate these effects such as reductions in and the timing of fertilizer use, agricultural intensification, tillage practices, and perennialization of fields and landscapes.[66-68]

Opportunities for Research

As indoor farming becomes more popular for food production, it is expected to have transformative effects on water, air, and soil, especially if brought to scale. These changes offer numerous current and future research opportunities. Here are just a few research questions worth examining:

- Exploring the impacts that indoor farming can have on shifting land use patterns with its consequent impacts on carbon sequestration, methane production, and nitrous oxide cycles.
- Exploring the impacts that indoor farming can have on water use and reductions in the effects of water run-off.
- Exploring the impacts that indoor farming can have on food production in arid regions and regions experiencing water stress or scarcity.
- Exploring the effects that reductions in soil erosion due to reduced agricultural activity can have on local eco-systems.
- Analyzing the carbon footprint of indoor farms located closer to metropolitan areas vs produce that travels hundreds or thousands of miles.
- Analyzing the biodiversity of water culture in hydroponic production systems vs soil based methods.
- Exploring the impacts that indoor farms can have on food production in urban areas, food deserts, and food security for a growing population.

In general, indoor agriculture is expected to grow significantly over the next 5-10 years[69,70] to supplement the production of fresh vegetables through open-field farming methods. This transformation of food production will have significant and potentially positive impacts on air, water, and soil.

Summary and Conclusions

The primary goal of this article was to introduce indoor farming in its many forms to researchers in the environmental sciences. With the advent of climate change, supply chain disruptions, increased transportation costs, and the desire to build sustainable systems, indoor farming is becoming an essential part of food production. The primary indoor farming methods include greenhouses and indoor vertical farms or plant factories. Greenhouses have the advantage of free sunlight to grow on one level at the expense of higher operating costs for heating and cooling. Indoor vertical farms, however, allow for growing on multiple levels, high levels of control, and water conservation but require more energy to operate for lighting and HVAC. Both approaches minimize several externalities related to air, soil, and water. Indoor farming reduces the point-source production of GHG emissions such as methane, nitrogen, and carbon dioxide. Indoor farming also mitigates the negative impacts of water run-off, soil erosion, pesticide use, and nutrient loading. Furthermore, indoor farming takes away motivation to over-use existing land for agriculture or to convert a very limited supply of arable land to agriculture. Allowing more lands to transform back to forest or be populated with perennials mitigates the release of CO_2 and promotes carbon sinking. Much research needs to be done to better understand the cumulative effects indoor farming can have on air, water, and soil. I encourage readers to consider framing interesting research questions related to their areas of specialization as a consequence of this relatively new method of farming.

AUTHOR'S NOTE

Dr. Stein is Associate Professor of Management Science and Information Systems in the business school at Penn State and serves as Executive Director of the Center of Excellence for Indoor Agriculture.

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Author Contributions

Eric Stein is the only contributor to this article. He facilitated the data collection, literature review, analysis and synthesis. The author drafted the manuscript based on the guidelines and the standards of the journal. All changes were made by the author at the request of the reviewers and the editor. In summary, all procedures and tasks contributing to the development of the manuscript were carried out solely by the author.

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