HYDROPONIC VERTICAL SYSTEMS: ENHANCING CLIMATE RESILIENCE, WATER EFFICIENCY, AND URBAN AGRICULTURE
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SISTEME VERTICALE HIDROPONICE: INTENSIFICAREA REZISTENȚEI LA CLIMĂ, EFICIENȚEI APEI ȘI AGRICULTURII URBANE

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ABSTRACT

This paper explores hydroponic vertical systems as a sustainable solution to modern agricultural challenges, particularly those posed by climate change. Hydroponics, a method of growing plants without soil using nutrient-rich water solutions, offers significant advantages over traditional farming. Vertical systems maximize space efficiency by growing plants in stacked layers, making them ideal for urban environments with limited space. These systems provide a controlled environment that mitigates the impacts of extreme weather, ensuring consistent crop production. The paper reviews various hydroponic techniques, including deep water culture, nutrient film technique, flood and drain, and drip irrigation. It highlights the efficiency of water use in hydroponics, crucial for areas facing water scarcity. Advanced technologies, such as sensors, automated nutrient delivery, and LED lighting, are employed to optimise growing conditions, enhance resource use efficiency, and improve crop yields. LED lights, in particular, offer energy efficiency, customizable spectra, and low heat output. Mathematical models are used to maximize plant development and resource efficiency, providing a framework for understanding plant-environment interactions. Despite high initial setup costs and the need for technical expertise, hydroponic systems present long-term economic and environmental benefits. This paper underscores hydroponic vertical systems' potential to revolutionize urban agriculture, ensuring food security and sustainability amidst climate change challenges.

REZUMAT

Această lucrare explorează sistemele verticale hidroponice ca o soluție durabilă la provocările agricole moderne, în special cele generate de schimbările climatice. Hidroponia, o metodă de cultivare a plantelor fără sol folosind soluție de apă bogată în nutrienți, oferă avantaje semnificative față de agricultura tradițională. Sistemele verticale maximizează eficiența spațiului prin creșterea plantelor stratificat, făcându-le ideale pentru mediile urbane cu spațiu limitat. Aceste sisteme oferă un mediu controlat care atenuează impactul vremii extreme, asigurând o producție constantă a culturilor. Lucrarea trece în revistă diferite tehnici hidroponice, inclusiv cultura în apă adâncă, tehnica filmului nutritiv, inundarea și scurgerea și irigarea prin picurare. Subliniază eficiența utilizării apei în hidroponie, crucială pentru zonele care se confruntă cu deficitul de apă. Tehnologiile avansate, cum ar fi senzorii, livrarea automată a nutrienților și iluminatul cu LED-uri, sunt folosite pentru a optimiza condițiile de creștere, a îmbunătăți eficiența utilizării resurselor și a îmbunătăți randamentul culturilor. LED-urile, în special, oferă eficiență energetică, spectre personalizabile și putere termică scăzută. Modelele matematice sunt folosite pentru a maximiza dezvoltarea plantelor și eficiența resurselor, oferind un cadru pentru înțelegerea interacțiunilor plante-mediu. În ciuda costurilor inițiale mari de instalare și a necesității de expertiză tehnică, sistemele hidroponice prezintă beneficii economice și de mediu pe termen lung. Această lucrare subliniază potențialul sistemelor verticale hidroponice de a revoluționa agricultura urbană, asigurând securitatea alimentară și sustenabilitatea în mijlocul provocărilor legate de schimbările climatice.

INTRODUCTION

One of the most important worldwide issues of the twenty-first century is climate change, which has a significant influence on many industries, including agriculture. Due to agriculture's natural sensitivity to weather, there are serious threats to global food security as a result of weather patterns becoming more unpredictable. Climate change has a wide range of consequences on agriculture, including changes in agricultural production, livestock health, and the occurrence of diseases and pests. For the purpose of creating plans to lessen negative effects and guarantee sustainable agricultural practices, it is essential to comprehend these implications (*El-Ghobashy et al., 2023; FAO, 2016; FAO, 2023a; Stein, 2021*).

One of the most direct effects of climate change on agriculture is the alteration in crop yields. Changes in temperature, precipitation patterns, and the increased frequency of extreme weather events such as droughts, floods, and heatwaves can severely affect crop productivity. Higher temperatures can accelerate crop maturation but also reduce the period of grain filling, leading to lower yields. For example, staple crops like wheat, maize, and rice are highly sensitive to temperature changes, with even slight increases potentially resulting in significant yield reductions (*Lobell et al., 2011*). Additionally, altered precipitation patterns can lead to water stress in some regions, while others may experience excessive rainfall, both of which can negatively impact crop growth (*FAO, 2023b*).

The distribution and prevalence of agricultural pests and diseases are influenced by climate change, potentially leading to increased crop and livestock losses. Warmer temperatures and higher humidity levels can create favourable conditions for pests and pathogens, resulting in more frequent and severe outbreaks (*Patterson et al., 2015*). For instance, the range of the European corn borer, a major pest for maize, is expected to expand northwards with rising temperatures, affecting areas previously unexposed to this pest. Similarly, changes in climate can alter the life cycles and population dynamics of many insect vectors, increasing the spread of plant and animal diseases.

The impacts of climate change on agriculture extend beyond biological effects, encompassing significant socio-economic dimensions. Reduced agricultural productivity can lead to higher food prices, increased food insecurity, and livelihood challenges for farmers, particularly in developing countries where agriculture is a primary source of income (*FAO, 2023b*). Smallholder farmers are especially vulnerable due to their limited capacity to adapt to changing conditions and invest in resilient agricultural practices.

Addressing the challenges posed by climate change to agriculture requires comprehensive adaptation and mitigation strategies. These include developing climate-resilient crop varieties, improving water management practices, adopting sustainable soil management techniques, and enhancing pest and disease control measures. Additionally, integrating advanced technologies such as precision agriculture or vertical farming, which uses data-driven approaches to optimise farming practices, can help mitigate the adverse effects of climate change (*Benke & Tomkis, 2017; Mir et al., 2022*).

Hydroponics, the method of growing plants without soil by using nutrient-rich water solutions, offers a promising solution to combat the adverse effects of climate change on crop production. As climate change alters weather patterns, increases the frequency of extreme weather events, and affects water availability, hydroponics provides a controlled environment for agriculture, mitigating many of these challenges (*Chang et al., 2018, Maucieri et al., 2017, Niu & Masabni, 2018*).

Vertical hydroponic systems represent a significant innovation in agricultural technology, aimed at maximizing space efficiency and resource use in plant cultivation. Unlike traditional horizontal farming, these systems grow plants in vertically stacked layers, which is particularly advantageous in urban environments with limited space (*Avgoustaki & Xydis, 2020; Despomier, 2013; FAO, 2022*).

The paper presents a review of the characteristics of hydroponic vertical systems, their advantages and disadvantages, as well a series of technical solution employed for implementing and operating these systems and turning them in means of combating climate changes effects on agriculture and supplying fresh food to the growing population, especially that clustered in urban areas.

MATERIALS AND METHODS

Hydroponic systems are typically housed in greenhouses or indoor environments where conditions such as temperature, humidity, and light can be tightly controlled. This control protects crops from extreme weather events like droughts, floods, and storms, which are becoming more frequent due to climate change (*Asha et al., 2023; Tusi & Shimazu, 2021*).

Hydroponics allows for continuous crop production throughout the year, regardless of external weather conditions. This stability is crucial as climate change leads to unpredictable growing seasons and affects traditional agricultural timelines (*Graves, 1983; Sharma et al., 2018*).

Hydroponic systems use water more efficiently than traditional soil-based agriculture. Water is recirculated in a closed-loop system, significantly reducing the amount needed for crop growth. This efficiency is particularly important as climate change exacerbates water scarcity in many regions (*Debnath & Mohiudin, 2020, Zhang et al., 2022*).

In traditional farming, a significant amount of water is lost to evaporation and runoff. Hydroponics minimizes these losses, ensuring that more water is available for plant uptake, which is critical in areas facing water shortages (*Carotti et al., 2023; Goldammer, 2019*).

In hydroponic systems, nutrients are delivered directly to plant roots in a soluble form, ensuring optimal uptake. This direct delivery can lead to faster growth rates and higher yields compared to traditional farming, which can be hindered by poor soil quality and nutrient availability affected by climate conditions. The controlled environment of hydroponic systems reduces the incidence of soil-borne diseases and pests. This reduction minimizes crop losses and the need for chemical pesticides, which can be harmful to the environment (*Gruda, 2020; Hosseinzadeh et al., 2017; Son et al., 2020*).

Hydroponics can be implemented in urban areas, utilizing spaces like rooftops, abandoned buildings, and vertical farms. This adaptability helps alleviate the pressure on rural agricultural land, which may be increasingly affected by climate change (*Dumitrescu et al., 2022; GVR, 2021*).

By decoupling crop production from arable land, hydroponics mitigates the impact of land degradation caused by climate change. This method ensures food production can continue even as fertile land becomes scarce.

Hydroponic farms can integrate renewable energy sources such as solar or wind power to run their systems, reducing reliance on fossil fuels and minimizing their carbon footprint. This integration is aligned with climate change mitigation strategies. These systems also allow precise control over the amount and type of fertilizers used, reducing the risk of over-fertilization and nutrient runoff, which can contribute to environmental pollution and greenhouse gas emissions (*Aiswarya & Vidhya, 2023; Cristea et al. 2024*).

They often use advanced technologies such as sensors, automated nutrient delivery, and data analytics to monitor and optimise growing conditions. These technologies enhance resource use efficiency and crop management, making agriculture more resilient to climate variability. Hydroponics can support the growth of a wide variety of crops, including those that might struggle in changing soil and climate conditions. This diversity can help stabilize food supply chains impacted by climate change (*Asher & Edwards, 1983; Charumathi et al., 2017; Cho et al., 2017; Hati & Singh, 2021*).

Hydroponic systems rely on a variety of technologies to optimise plant growth, improve efficiency and ensure sustainability (*Nguyen et al., 2016*).

Irrigation and nutrient delivery systems

Depending on the manner of irrigating and delivering nutrient to the crops, hydroponics is divided in various types, as follows:

1. **Deep water culture**

Deep Water Culture (Figure 1) or direct water culture is a type of hydroponic farming method in which the roots of the plants are continually suspended in nutrient-rich, oxygenated water solution (*Sambo et al., 2019*).

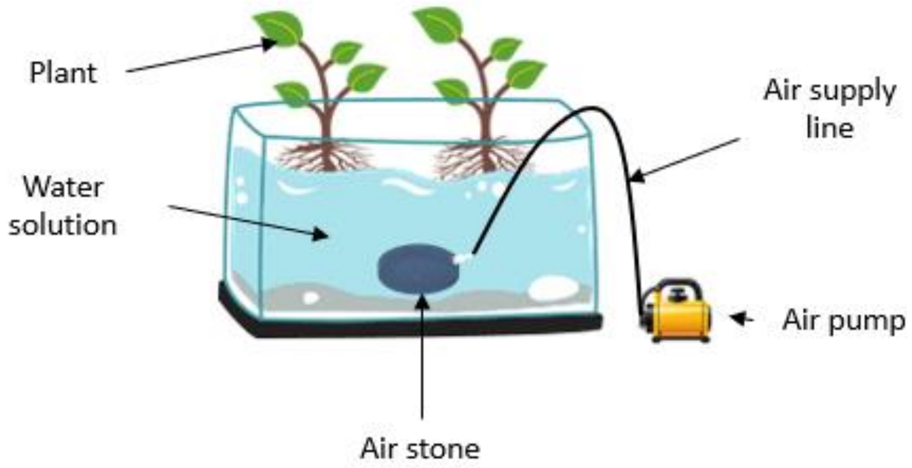


Fig. 1 – Deep water culture plant growing
(*adapted from Syed et al., 2021*)

Deep water culture works in the following manner:

- A reservoir is filled with water – nutrient solution, plants are placed in net pots as such or filled with an inert substrate (clay pebbles, hydro cocos) and immersed in the water – nutrient mixture;

- An air pump and air stone are used to oxygenate the water mixture, ensuring that plant roots receive adequate oxygen. This prevents roots from rotting and promotes healthy plant growth;
- The water nutrient solution is constantly monitored and adjusted as to maintain the correct pH and nutrient levels;
- The plants are continuously submerged in the nutrient solution thus allowing them to take up water and nutrients in an efficient manner.

2. Nutrient Film Technique (NFT)

Nutrient Film Technique – NFT (Figure 2) is a popular hydroponic method that involves a continuous flow of nutrient-rich water over the roots of plants. This technique is widely used due to its efficiency, simplicity, and effectiveness in providing nutrients to plants (*Guzman-Valvidia et al., 2019*).

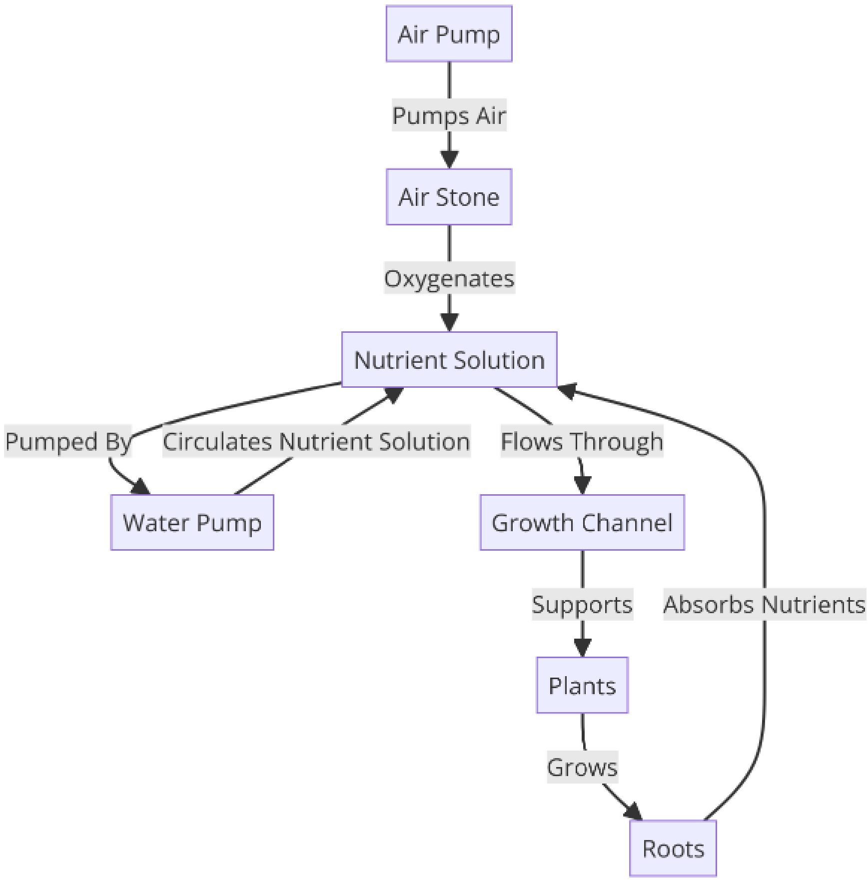


Fig. 2 – Nutrient film technique plant growing diagram

Nutrient film technique works in the following manner:

- Plants are places in an inclined channel type growth tray made of inert materials;
- A pump continuously delivers the nutrient-rich water solution from the reservoir to the growth channels;
- The solution flows down the slope inside the growth channel, forming a thin film of nutrient-rich water that is absorbed by the roots of plants;
- The roots of plants are constantly exposed to air as well to the nutrient solution, thus receiving the required oxygen for a healthy development;
- After flowing through the growth channels, the excess nutrient solution (that is not absorbed by the plants) drains back into the reservoir and is recirculated.

3. Flood and drain

Flood and Drain (Figure 3) is a system that involves the periodic flooding and draining of the nutrient solutions. Basically, there are two phases of its operation. The **flood** is when the water and nutrients flow the growing areas, flowing over the plants' roots, followed by the second phase – **draining** (*Putra & Yuliado, 2015; Clyde-Smith & Campos, 2023*).

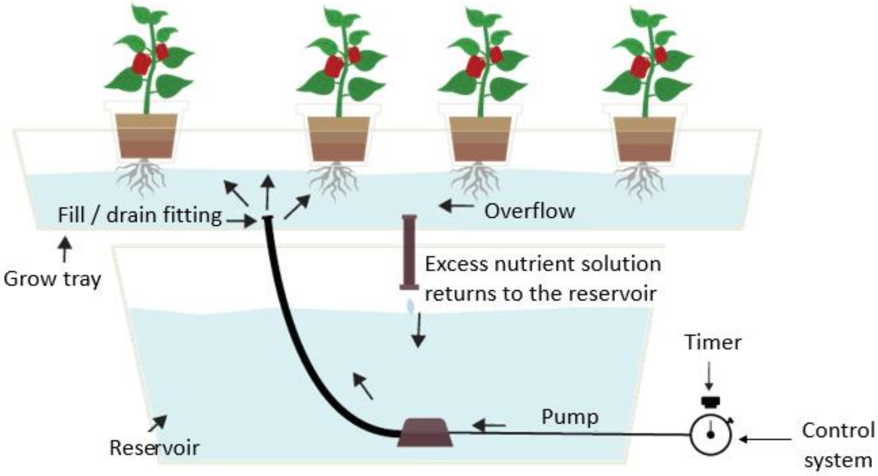


Fig. 3 – Flood and drain technique plant growing
(*https://www.trees.com/gardening-and-landscaping/ebb-and-flow-hydroponics*)

Flood and drain system works in the following manner:

- Plants are placed in wire pots / mineral substrate in a growth tray with one or multiple openings at the bottom part, situated above a water tank;
- The water tank is filled with water – nutrient solution and through the means of a pump is distributed to the grow tray at intervals regulated by a timer;
- After a preset time of flooding the growth tray, the opening (s) of the growth tray allows the excess water to drain in the reservoir below, thus leaving the plants with the ability to intake oxygen through the roots;
- After a preset time, the flooding process resumes, followed again by draining of the growth trays in the determined cycle.

4. Drip irrigation

Drip irrigation (Figure 4) is a type of micro-irrigation system that has the potential to save water and nutrients by allowing water to drip slowly to the roots of plants, either from above the substrate surface or buried below the surface (*Perez et al., 2024*).

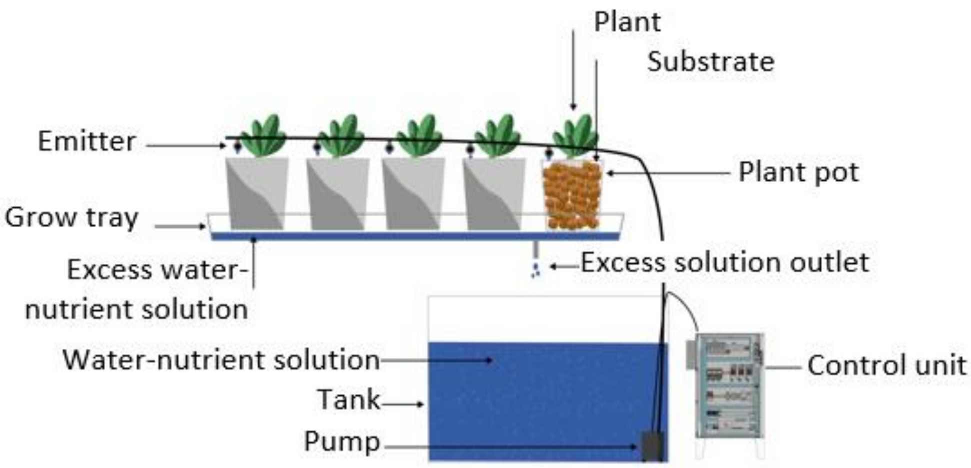


Fig. 4 – Flood and drain technique plant growing
(*adapted from https://hydroplanner.com/blog/hydroponics-drip-system-EN*)

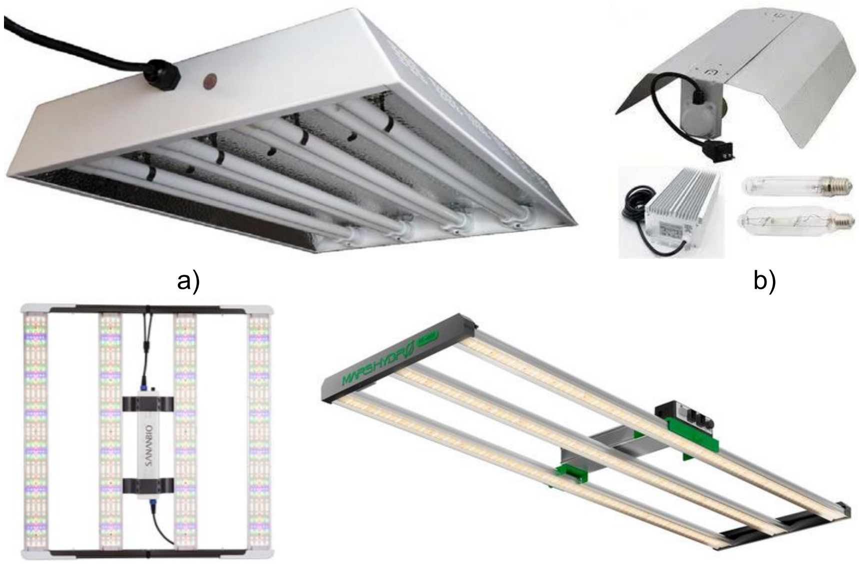
Drip irrigation hydroponic systems work in the following manner:

- Plants are placed in individual containers or in a larger growth tray, supported by a growing medium (substrate) such as clay pebbles, coco coir, perlite, or rock wool.
- A tank is filled with the nutrient-rich water solution.
- A water pump is used to transport the nutrient solution from the reservoir to the plants.

- A network of hoses and drip emitters deliver the nutrient solution directly to the base of each plant.
- An automation system is used to control the pump, ensuring the nutrient solution is delivered at regular intervals.
- The excess water-nutrient solution is collected back in the reservoir.

Lighting systems

Lighting systems for hydroponics are a critical component of indoor gardening and plant cultivation, enabling growers to simulate natural sunlight and provide the necessary light spectrum for photosynthesis. In hydroponics, where plants are grown without soil, optimizing light conditions is essential to promote healthy growth, flowering, and fruiting. These artificial lighting systems replicate the sun’s intensity and spectrum, allowing plants to grow indoors all year-round, regardless of outdoor weather conditions. Different types of growth lights (Figure 5), such as fluorescent, high-intensity discharge (HID), and light-emitting diode (LED) lights, are used to meet the specific needs of various plant species and growth stages. Fluorescent lights are often favoured for seedlings and leafy greens due to their lower intensity and cooler operation, while HID lights, including metal halide (MH) and high-pressure sodium (HPS), offer higher intensity suitable for larger, flowering plants (*Arcel et al., 2021; Avgoustaki & Xydis, 2021; Bures et al., 2018; Jager, 2024; Smith, 1982*).



a) b) c)

Fig. 5 – Growth lights used for hydroponic systems

a) – fluorescent lights (*https://www.hydrocentre.com*), b) – HID lights (*https://www.nosoilsolutions.com/*), c) – LED lights (*https://www.sananbiofarm.com/; https://marshydro.eu/*)

LED lights have become increasingly popular in recent years due to their energy efficiency, long lifespan, and customizable light spectrum, which can be tailored to the precise needs of the plants. Properly managing the duration, intensity, and spectrum of light ensures that hydroponic plants receive optimal conditions to maximize growth and yields, making lighting systems a pivotal factor in the success of hydroponic gardening (*Jin et al., 2023; Matysiak et al., 2021; Najera et al., 2022; Sellaro et al., 2010*).

The **advantages** of using LED lights in hydroponic systems are listed as follows (*Lobiuc et al., 2017; Pennisi et al., 2019; Phum et al., 2024; Tharun & Padmasine, 2023*):

- **Energy efficiency** - LED lights are highly energy-efficient compared to traditional lighting systems such as fluorescent and high-intensity discharge (HID) lights. They consume less electricity while providing the same or even higher levels of light output, resulting in lower energy bills and reduced environmental impact.
- **Long lifespan** - LED lights have a significantly longer lifespan than other types of grow lights. They can last up to 50,000 hours or more, which means fewer replacements and lower maintenance costs over time.
- **Customizable light spectrum** - LED lights can be engineered to emit specific wavelengths of light that are most beneficial for plant growth. This allows growers to tailor the light spectrum to the needs

of their plants at different growth stages, optimizing photosynthesis and improving overall plant health and yields.

- **Low heat output** - LED lights produce much less heat compared to HID and fluorescent lights. This reduces the risk of heat stress and burn damage to plants, allowing the lights to be placed closer to the plants. Additionally, lower heat output minimizes the need for additional cooling systems, saving on energy costs.
- **Compact and flexible design** - LED grow lights are available in a variety of shapes and sizes, making them adaptable to different growing spaces. Their compact and flexible design makes it easier to install them in tight or uniquely shaped areas, maximizing the use of available space.
- **Improved growth and yields** - Due to their ability to provide a tailored light spectrum, LED lights can enhance plant growth, improve flowering and fruiting, and increase yields. The precise control over light wavelengths ensures that plants receive the optimal light conditions for each stage of growth.
- **Durability and safety** - LED lights are more durable and robust compared to other lighting options. They are less prone to breakage and can withstand environmental fluctuations better. Additionally, they do not contain harmful substances like mercury, making them safer for both the grower and the environment.
- **Instant On/Off** - LED lights reach full brightness instantly, unlike some HID lights that require a warm-up period. This instant on/off capability is beneficial for controlling light cycles precisely, which is important for maintaining consistent growth conditions.
- **Lower light degradation** - LEDs maintain their light output over a longer period, experiencing less degradation compared to other types of grow lights. This means that the intensity and quality of light remain more consistent, contributing to stable and reliable plant growth.
- **Long-term cost-effectiveness** - Although the initial investment for LED lights may be higher than for other types of grow lights, their energy efficiency, long lifespan, and lower maintenance costs make them a more cost-effective option in the long term.

The **disadvantaged** of using LED lights in hydroponic systems are considered as follows (*Naz et al., 2021; Phum et al., 2024; Tharun & Padmasine, 2023*):

- **Initial Cost** - LED lights generally have a higher upfront cost compared to other types of grow lights like fluorescent and HID lights. This initial investment can be a significant barrier for small-scale growers or those new to hydroponics.
- **Light Intensity** - Although LED technology has improved, some LED grow lights may not provide the same level of light intensity as high-intensity discharge (HID) lights. This can be a disadvantage for plants that require very high light levels, such as some fruiting and flowering plants.
- **Spectrum Limitations** - Not all LED lights offer a full-spectrum light that mimics natural sunlight. Some cheaper models may provide a narrow spectrum that isn't suitable for all stages of plant growth. Ensuring that the LED lights cover the necessary wavelengths for photosynthesis and development is crucial, which can be challenging with lower-quality products.
- **Heat Distribution** - While LED lights produce less heat than HID lights, the heat they do generate is often concentrated in a smaller area. Without proper heat sinks or cooling systems, this can potentially cause localized heating issues, affecting plant health if the lights are placed too close.
- **Complexity in Selection** - The market for LED grow lights is vast, with many different models and specifications. Choosing the right LED light can be complex and confusing, especially for beginners. The need to understand specifications such as light spectrum, intensity, and coverage area can be overwhelming.
- **Lifespan Variability** - Although LEDs have a long lifespan, their actual longevity can vary significantly based on the quality of the components and manufacturing. Poor-quality LEDs may degrade faster, leading to reduced light output over time.
- **Electrical Requirements** - High-power LED systems can require specific electrical setups, such as additional wiring or circuit adjustments, to handle their power needs safely and efficiently. This can add to the installation complexity and cost.
- **Limited Penetration** - LED lights often have less light penetration compared to HID lights. This means that the light may not reach the lower parts of larger plants effectively, potentially impacting the growth of lower leaves and branches.

- **Potential for Over-Saturation** - LED lights can sometimes provide too much light in specific wavelengths, leading to issues like light bleaching or nutrient imbalances. Plants may develop symptoms of overexposure if the light intensity and spectrum are not carefully managed.
- **Dependence on Technology** - LED systems rely on electronic components and sophisticated technology, which can sometimes lead to issues with reliability and the need for technical support. Problems with drivers, diodes, or other electronic parts can necessitate repairs or replacements, which can be costly and time-consuming.

RESULTS

Developing and using mathematical models in hydroponic systems has become essential for maximising plant development, resource efficiency, and environmental control. To attain optimal efficiency and yield, hydroponic farming needs careful management over a number of parameters. A foundation for comprehending and forecasting the intricate relationships between plant physiology and environmental variables is provided by mathematical models. These models include kinetic models that depict rates of nutrient intake as well as dynamic and eco-physiological models that mimic the time-dependent behaviour of plant growth and interactions with the environment.

Dynamic models can be used to determine the optimal root zone temperature (RZT) for different growth stages, ensuring that plants receive the right amount of nutrients and water throughout their lifecycle. Eco-physiological models help in understanding how plants respond to changes in nutrient availability, temperature, and other environmental factors, which is essential for optimizing nutrient formulations and irrigation schedules. The use of Artificial Neural Networks (ANNs) and machine learning techniques has further enhanced the modelling of hydroponic systems by enabling the prediction of plant growth and yield based on historical data and current environmental conditions. These models are particularly effective in handling non-linear relationships and can adapt to new data, making them suitable for the dynamic environments of hydroponic farming.

Below are presented a series of mathematical models that contribute to the various approaches of estimating and controlling plant growth using hydroponic systems.

1. Dynamic response of plant growth (*Aji et al., 2020*)

$$WR(t) = \frac{\Delta W}{\Delta t} \text{ , [\%]} \tag{1}$$

This model determines the response of plant growth (*WRt*) measuring the sensitivity of changes in plant weight (*ΔW*, [g]) in relation to the change in time (*Δt*, [d]).

The Dynamic Response of Plant Growth model, represented by Equation (1), quantifies the sensitivity of plant growth in response to changes in environmental conditions over time. This model is pivotal for predicting how plants will respond to varying nutrient levels and environmental factors, enabling precise adjustments to optimise growth rates. By measuring the change in plant weight over time, this model helps in identifying the most effective growth conditions and allows for dynamic adjustments to maintain optimal growth.

2. Ion concentration in the culture crop solution model (*Carmassi et al., 2004*)

$$U = V \times C_{n-1} + V_R \times C_R - V \times C_n \text{ , [mmol]} \tag{2}$$

This model derives from the balance equation for nutrient by the plants (U) over the period between n and $n-1$ [days]. V is the volume of the system [l], C is the total ionic concentration of the nutrient solution [mM] and V_R [l] and C_R [mM] represent the volume and ionic concentration of the nutrient solution added to the system in a given interval.

The model depicted in Equation (2) focuses on the nutrient balance within the hydroponic solution. This model ensures that plants receive the appropriate levels of nutrients by monitoring and adjusting the ionic concentration of the solution. The accurate management of nutrient levels is crucial for preventing deficiencies and toxicities, which can significantly impact plant health and yield. This model helps in maintaining a stable nutrient environment, which is essential for the continuous and healthy growth of plants in hydroponic systems.

3. Mathematical model for monitoring carbon dioxide concentration (*Laktionov et al., 2018*)

$$\varphi_{CO_2}^{sour} - \varphi_{CO_2}^{vent} - \varphi_{CO_2}^{phot} = 0 \text{ , [ppm]} \quad (3)$$

where $\varphi_{CO_2}^{sour}$ is the amount of carbon dioxide the enters the system; $\varphi_{CO_2}^{vent}$ is the amount of carbon dioxide lost from the system through ventilation and $\varphi_{CO_2}^{phot}$ is the amount of carbon dioxide consumed by the plants through photosynthesis.

This model is based on the distribution of carbon dioxide occurring in two simultaneous processes: the movement on CO_2 in an opposite direction compared to the concentration gradient and the movement caused by air currents. Carbon dioxide is a critical component of photosynthesis, and its optimal concentration can significantly influence plant growth. This model accounts for the carbon dioxide entering the system, losses due to ventilation, and consumption by plants. By ensuring a balanced carbon dioxide level, this model supports the enhancement of photosynthetic efficiency and overall plant productivity.

4. Computational fluid dynamics techniques model (*Rezvani et al., 2021*)

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \times (\partial\bar{u}\phi) = \nabla \times (\Gamma\nabla\phi) + S_\phi \quad (4)$$

where ρ is the density (kg m^{-3}), t is time, ∇ is divergence operator, and ϕ represents the concentration of the dimensionless transported quantity (momentum, mass, anergy), $\bar{u}$ (m s^{-1}) is the component of the velocity vector, Γ represents the diffusion coefficient (m^{2}s^{-1}) and S_ϕ is the source term indicating the changes in the amount of manner in the transfer.

This model is essential for understanding the distribution and flow of the nutrient solution, which directly affects nutrient availability to plant roots. By modelling the movement and concentration of the solution, this approach helps in designing efficient delivery systems that ensure uniform nutrient distribution and prevent issues such as stagnation or uneven nutrient uptake.

5. Water uptake model (WUS) (*Lopez Mora et al., 2024*)

$$ET_o = [0.408\Delta(R_n - G) + 37u_2\gamma(e_s - e_a) \times (T + 273)^{-1}][\Delta + \gamma(1 + u_2C_d)]^{-1} \text{, [mmh}^{-1}\text{]} \quad (5)$$

where: Δ [*KPA* x *C^{o-1}*] represents the slope of the relationship between the saturation vapor pressure and temperature; R_n and G [MJm^{-2}h^{-1}] represent the net variation at crop surface, respectively substrate heat flux at substrate surface; γ [*KPAC^{o-1}*] represents the psychometric constant; u_2 [ms^{-1}] is the average hourly wind speed; e_s-e_a [KPa] is the air's vapour pressure deficit; T [^{o}C] is the hourly temperature of the air; C_d [sm^{-1}] represents the day and night factor (0.24 for day hours and 0.96 for night hours).

This model is used to calculate crop Evapotranspiration (ET_o) in hourly periods [mmh^{-1}] and incorporates various environmental factors such as temperature, wind speed, and vapor pressure deficit to calculate the hourly water uptake by plants. By optimizing water use, this model supports sustainable practices in hydroponic farming, which is particularly important in regions facing water scarcity.

These mathematical models collectively contribute to the precision and efficiency of hydroponic systems. By enabling detailed monitoring and control of various factors affecting plant growth, they support the development of more resilient and productive agricultural practices. The integration of these models with advanced technologies such as sensors and automation further enhance their applicability, making hydroponic systems a viable solution for sustainable agriculture in the face of climate change.

The implementation of hydroponic systems in agriculture presents a myriad of advantages and challenges. As the agricultural industry seeks sustainable and efficient methods to address the growing concerns of climate change and food security, hydroponic systems offer a promising solution (*Lubna et al., 2022; Magwaza et al., 2020; Sarkar & Majumer, 2015*).

Table 1 outlines the numerous benefits of hydroponic systems, such as controlled environment agriculture, efficient water use, and enhanced crop yields. Conversely, Table 2 highlights the potential drawbacks associated with these systems, including high initial setup costs and the need for technical expertise. Together, these tables offer a balanced view of the hydroponic approach, supported by recent literature, and aid in evaluating its viability for future agricultural practices.

Table 1

Advantages of hydroponic systems

Advantage	References
Controlled Environment Agriculture	*Al-Kodmany, 2018; Kozai, 2018; Kumar & Singh, 2024*
Efficient Water Use	*Park & Williams, (2024); Savvas, 2003; Kozai, 2018; Verdoliva et al., 2021; Zimmermann & Fisher, 2020; Clyde-Smith & Campos, 2023*
Enhanced Crop Growth and Yield	*Butt, 2010; Etesami et al., 2023; Kozai, 2018;*
Adaptability to Urban and Unconventional Spaces	*Al-Kodmany, 2018; Despommier, 2010; Richa et al., 2020*
Energy and Resource Efficiency	*Graamans et al., 2018; Kozai, 2018; van Straten et al., 2011*
Innovative Crop Management	*van Straten et al., 2011*
Reduced Need for Chemical Pesticides	*Jones, 2014; Resh, 2012; Velazquez-Gonzalez et al., 2022*
Consistent and Predictable Crop Production	*Butturini & Marcelis, 2019; Kozai, 2018*
Reduced Land Use	*Al-Kodmany, 2018; Despommier, 2010; Van Delden et al., 2021*
Potential for Higher Nutritional Quality	*Barbosa et al., 2015; Pantanella et al., 2012*

Table 2

Disadvantages of hydroponic systems

Disadvantage	References
High Initial Setup Costs	*Kozai, 2018; Resh, 2012; van Tuiji et al., 2018*
Technical Expertise Required	*Delaide et al., 2016; Jones, 2014; Resh, 2012*
Dependency on Electricity	*Graamans et al., 2018; Kozai, 2018; Promratrak L., 2017*
Potential for Waterborne Diseases	*Jones, 2014; Savvas, 2003; van Tuiji et al., 2018*
High Energy Consumption	*Graamans et al., 2018; Promratrak L., 2017; van Straten et al., 2011; Velazquez-Gonzalez et al., 2022; Xydis et al., 2017*
Limited Crop Variety	*Barbosa et al., 2015; Butt, 2010; Promratrak L., 2017*
Continuous Monitoring Needed	*Jones, 2014; Resh, 2012; van Tuiji et al., 2018*
System Failures Can Be Catastrophic	*Butt, 2010; Delaide et al., 2016; Jones, 2014*
Limited Organic Certification	*Butturini & Marcelis, 2019; Delaide et al., 2016; Resh, 2012;*
Nutrient Solution Management	*Jones, 2014; Promratrak L., 2017; Savvas, 2003; Van Delden et al., 2021*
Limited Scalability for Certain Crops	*Butt, 2010; Promratrak L., 2017*
High Initial Learning Curve	*Delaide et al., 2016; Jones, 2014; Resh, 2012*
Need for High-Quality Water	*Savvas, 2003; van Tuiji et al., 2018*
High Operational Costs	*Graamans et al., 2018; Kozai, 2018*

In summary, hydroponic systems present a transformative approach to modern agriculture, offering substantial benefits such as efficient water use, enhanced crop yields, adaptability to urban environments, and reduced need for chemical pesticides, as highlighted in Table 1. However, these advantages come with notable challenges, as detailed in Table 2, including high initial setup costs, the requirement for technical expertise, and dependency on electricity. By weighing these pros and cons, stakeholders can make informed decisions about implementing hydroponic systems. This balanced perspective underscores the potential of hydroponics to contribute to sustainable and resilient agricultural practices, particularly in the face of global challenges like climate change and urbanization.

CONCLUSIONS

By analysing hydroponic vertical systems, the following conclusions can be drawn:

- the implementation of hydroponic vertical systems offers a significant solution to the challenges posed by climate change on traditional agriculture. These systems provide a controlled environment that shields crops from extreme weather events, ensuring stable crop production irrespective of external climatic conditions;
- hydroponic systems utilize water more efficiently compared to conventional soil-based agriculture. by recirculating water in a closed-loop system, these systems significantly reduce water usage, making them particularly beneficial in regions facing water scarcity. This efficient water use is crucial as climate change exacerbates water shortages globally;

- the direct delivery of nutrients to plant roots in hydroponic systems ensures optimal nutrient uptake, leading to faster growth rates and higher yields. The controlled environment minimizes the occurrence of soil-borne diseases and pests, reducing the need for chemical pesticides and promoting healthier crop production;
- vertical hydroponic systems maximize space utilization by growing plants in vertically stacked layers. This innovation is especially advantageous in urban environments where space is limited, contributing to urban agriculture and reducing pressure on rural agricultural lands;
- these systems can integrate renewable energy sources such as solar or wind power, reducing reliance on fossil fuels and minimizing their carbon footprint. This integration aligns with global climate change mitigation strategies and promotes sustainable agricultural practices;
- hydroponic systems employ advanced technologies such as sensors, automated nutrient delivery, and data analytics to monitor and optimise growing conditions. These technologies enhance resource use efficiency, making agriculture more resilient to climate variability and improving overall productivity;
- the development and use of mathematical models in hydroponic systems are essential for maximizing plant development and resource efficiency. These models help in understanding and predicting the complex interactions between plant physiology and environmental variables, leading to better management practices and higher yields;
- the use of LED lights in hydroponic systems offers several advantages, including energy efficiency, customizable light spectra, and low heat output. LED lights can be tailored to meet the specific needs of different plant species and growth stages, ensuring optimal growth conditions and improving crop yields;
- despite the high initial setup costs, hydroponic systems are cost-effective in the long term due to their efficiency and reduced operational costs. The precise control over growing conditions results in consistent and predictable crop production, contributing to food security;
- by minimizing water and nutrient runoff, hydroponic systems reduce environmental pollution. Additionally, the reduced need for chemical pesticides and fertilizers lessens the impact on surrounding ecosystems, promoting more sustainable agricultural practices;
- the adoption of hydroponic systems faces several challenges, including the need for technical expertise, continuous monitoring, and high initial setup costs. Addressing these challenges requires investment in education and training, as well as support from governmental and non-governmental organizations to promote the adoption of hydroponic farming;
- hydroponic vertical systems hold great potential for the future of agriculture, particularly in urban areas. as technology advances and becomes more accessible, these systems are likely to play a critical role in ensuring food security and sustainability in the face of climate change.

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REFERENCES

[1] Aishwarya, J.M., Vidhya, R. (2023). Study on the Efficiency of a Hydroponic Treatment for Removing Organic Loading from Wastewater and Its Application as a Nutrient for the “Amaranthus campestris” Plant for Sustainability. *Sustainability, 15*, 7814, https://doi.org/10.3390/su15107814

[2] Al-Kodmany, K. (2018). The Vertical Farm: A Review of Developments and Implications for the Vertical City. *Buildings, 8(2),* 24, https://doi.org/10.3390/buildings8020024

[3] Aji, G.K., Hatou, K., Morimoto, T. (2020). Modeling the Dynamic Response of Plant Growth to Root Zone Temperature in Hydroponic Chili Pepper Plant Using Neural Networks. *Agriculture, 10,* 234. https://doi.org/10.3390/agriculture10060234

[4] Arcel, M. M., Lin, X., Huang, J., Wu, J., Zheng, S. (2021). The application of LED illumination and intelligent control in plant factory, a new direction for modern agriculture: A Review. *Journal of Physics: Conference Series. 1732*, 012178. doi:10.1088/1742-6596/1732/1/012178.

[5] Asha S. V., Agarwal S., Dubey H., Jain L C., (2023). A study on hydroponic farming. *IJFMR, Vol. 5, Issue 2*, 23022286, E-ISSN: 2582-2160

[6] Asher, C. J., and Edwards, D. G. (1983). “Modern solution culture techniques” in *Inorganic plant nutrition*. eds. A. Pirson and M. H. Zimmermann (Berlin, Heidelberg: Springer), 94–119.

[7] Avgoustaki, D.D., Xydis, G., (2020). Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resource Savings. *Sustainability, 12*, 1965

[8] Avgoustaki, D.D., Xydis, G., (2021). Energy cost reduction by shifting electricity demand in indoor vertical farms with artificial lighting. *Biosystems Engineering, Volume 211,* 219-229, https://doi.org/10.1016/j.biosystemseng.2021.09.006

[9] Barbosa, G. L., Gadelha, F. D. A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., & Halden, R. U. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International Journal of Environmental Research and Public Health, 12(6)*, 6879-6891

[10] Benke, K., and Tomkins, B. (2017). Future food-production systems: vertical farming and controlled-environment agriculture. *Sustain. Sci. Pract. Policy 13*, 13–26. doi: 10.1080/15487733.2017.1394054

[11] Bures, S., Urrestarazu Gavilán, M., Kotiranta, S. (2018). Artificial lighting in agriculture [online]. *Horticulture Library*, available at https://www.valoya.com/artificial-lighting-in-agriculture/ (accessed on 23.05. 2024)

[12] Butt, S. J. (2010). Hydroponic Green Farming Initiative: Report and Case Study. *United Nations Development Programme*

[13] Butturini, M., & Marcelis, L. F. M. (2019). Vertical Farming in Controlled Environment Agriculture: Influence of Environmental Factors on Yield and Resource Use Efficiency of Leafy Greens. *Acta Horticulturae, 1266*, 333-342

[14] Carmassi, G., Maggini, R., Incrocci, L. (2004). Modelling Ion Concentration in the Culture Solution of Closed-Loop Hydroponics. *Acta Hort. 654*, ISHS.

[15] Carotti, L., Pistilo, A., Zauli, I., Meneghello, D., Martin, M., Pennisi, G., Gianquinto, G., Orsini, F. (2023). Improving water use efficiency in vertical farming: Effects of growing systems, far-red radiation and planting density on lettuce cultivation. *Agricultural Water Management. Volume 285, 1,* 108365, https://doi.org/10.1016/j.agwat.2023.108365

[16] Chang, C.L., Hong, G.F., Fu, W.L., (2018). Design and implementation of a knowledge-based nutrient solution irrigation system for hydroponic applications. *Trans. Asabe, 61*, 369–379

[17] Charumathi, S., Kaviya, R. M., Kumariyarasi, J., Manisha, R., and Dhivya, P. (2017). Optimization and control of hydroponics agriculture using IOT. *Asian J. Appl. Sci. Technol. 1*, 96–98

[18] Cho, W. J., Kim, H.-J., Jung, D. H., Kang, C. I., Choi, G.-L., and Son, J.-E. (2017). An embedded system for automated hydroponic nutrient solution management. *Trans. ASABE 60*, 1083–1096. doi: 10.13031/trans.12163

[19] Clyde-Smith, D., Campos, L.C., (2023). Engineering Hydroponic Systems for Sustainable Wastewater Treatment and Plant Growth. *Appl. Sci., 13*, 8032. https://doi.org/10.3390/app13148032

[20] Cristea, M., Vladut, N.V., Ungureanu, N. (2024) Using solar energy as non-conventional alternative energy in small and medium-sized farms, *INMATEH-Agricultural Engineering, Volume 72, No. 1,* pp. 631-643, https://doi.org/10.35633/inmateh-72-56

[21] Debnath S., Mohiudin G. (2020). Irrigation and Fertigation in Protected Cultivation, In: Protected Cultivation and Smart Agriculture, New Delhi Publishers, pp. 40-54. ISBN: 978-81-948993-2-7, doi: 10.30954/NDP-PCSA.2020.5

[22] Delaide, B., Goddek, S., Gott, J., Soyeurt, H., & Lambert, S. (2016). Lettuce (Lactuca sativa L. var. Sucrine) Growth Performance in Complemented Aquaponic Solution Outperforms Hydroponics. *Water, 8(10),* 467

[23] Despomier D. (2010). The vertical farm – Feeding the world in the 21st century. Thomas Dunne Books. ISBN: 978-0-312-61139-2

[24] Despomier D., (2013). Farming up the city: The rise of urban vertical farms. *Trends Biotechnol. 31*, 388–389

[25] Dumitrescu, L., Veringa, D., Matche, M.G., Vladutoiu, L.C. (2022). Preliminary results of the analysis of the main microclimate factors in an urban farm module, *INMATEH-Agricultural Engineering, Volume 67, No. 2,* pp. 278-284, https://doi.org/10.35633/inmateh-67-28

[26] El Ghobashy, H., Shaban, Y., Okasha, M., El-Reheem S.A., Abdelgawad, M., Ibrahim, R., Ibrahim, H., Abdelmohsen, K., Awad, M., Cottb., Elmeadawy M., Fathy, W., El-Sayed, K. (2023). Development and evaluation of a dual-purpose machine for chopping and crushing forage crops, *Heliyon, Vol. 9, Issue 4*, https://doi.org/10.1016/j.heliyon.2023.e15460

[27] Etesami, H., Jeong, B.R., Glick, B.R. (2023). Biocontrol of plant diseases by Bacillus Spp. *Physiological and Molecular Plant Pathology, Volume 126*, 102048, https://doi.org/10.1016/j.pmpp.2023.102048

[28] FAO. (2016). The state of food and agriculture. Climate change, agriculture and food security. ISBN 978-92-5-109374-0, Download http://www.fao.org/3/a-i6030e.pdf (accessed on 14.05.2024)

[29] FAO. (2023a). Land Use. In: FAOSTAT. Rome. https://www.fao.org/faostat/en/#data/RL Download: https://doi.org/10.4060/cc8166en-fig59 (accessed on 14.05.2024)

[30] FAO. (2023b). World Food and Agriculture – Statistical Yearbook 2023. Rome. https://doi.org/10.4060/cc8166en

[31] FAO, Rikolto and RUAF, (2022). Urban and peri-urban agriculture sourcebook – From production to food systems. Rome, FAO and Rikolto. https://doi.org/10.4060/cb9722en

[32] Goldammer T. (2019). Greenhouse Management - A Guide to Operations and Technology, Apex Publishers, ISBN (13): 978-0-9675212-4-4

[33] Graamans, L., van den Dobbelsteen, A., Meinen, E., & Stanghellini, C. (2018). Plant Factories, Crop Transpiration and Energy Balance. *Agricultural Systems, 153*, 138-147

[34] Graves, W. R. (1983). Hydroponic Plant Culture as a Method for Studying Plant Mineral Nutrition. *HortScience, 18(5),* 595-598

[35] Gruda, N.S. (2020). Advances in horticultural soilless culture. Burleigh Dodds Science Publishing. 442 pages, e-ISBN:9781003048206, https://doi.org/10.1201/9781003048206

[36] GVR. (2021). Hydroponics Market Size, Share & Trends Analysis Report By Type, By Crop Type (Tomatoes, Lettuce, Peppers, Cucumbers, Herbs, and Others), By Crop Area, By Region, And Segment Forecasts, 2024 – 2030. Available online: https://www.grandviewresearch.com/industry-analysis/hydroponics-market/methodology (accessed on 10 May 2024)

[37] Guzmán-Valdivia, C.H., Talavera-Otero, J., Désiga-Orenday, O. (2019). Turbulent Kinetic Energy Distribution of Nutrient Solution Flow in NFT Hydroponic Systems Using Computational Fluid Dynamics. *AgriEngineering, 1,* 283-290. https://doi.org/10.3390/agriengineering1020021

[38] Hati, A.J., Singh, R.R., (2021). Smart Indoor Farms: Leveraging Technological Advancements to Power a Sustainable Agricultural Revolution. *AgriEngineering, 3*, 47

[39] Hosseinzadeh, S., Verheust, Y., Bonarrigo, G., and Van Hulle, S. (2017). Closed hydroponic systems: operational parameters, root exudates occurrence and related water treatment. *Rev. Environ. Sci. Biotechnol. 16*, 59–79. doi: 10.1007/s11157-016-9418-6

[40] Jager S., (2024). Vertical farming (plant factory with artificial lighting) and its produce: consumer insights, *Current Opinion in Food Science. Volume 56,* 101145

[41] Jin, W., Formiga Lopez, D., Heuvelink, E., Marcelis L.F.M. (2023). Light use efficiency of lettuce cultivation in vertical farms compared with greenhouse and field. *Food Energy Secur. 12*: e391. https://doi.org/10.1002/fes3.391

[42] Jones, J. B. (2014). Hydroponics: A Practical Guide for the Soilless Grower. CRC Press.

[43] Kozai, T. (2018). "Smart Plant Factory: The Next Generation Indoor Vertical Farms." Springer. E-ISBN 978-981-13-1065-2. https://doi.org/10.1007/978-981-13-1065-2

[44] Kumar, P., Singh, J. (2024). Hydroponic: An Eco-friendly Future. In: Kumar, N. (eds) Hydroponics and Environmental Bioremediation. Springer Water. Springer, Cham. https://doi.org/10.1007/978-3-031-53258-0_9

[45] Laktionov, I., Vovna, O., Cherevko, O., Kozlovskaya, T. (2018). Mathematical model for monitoring carbon dioxide concentration in industrial greenhouses. *Agronomy Research 16(1),* 134-146, https://doi.org/10.15159/AR.17.074

[46] Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate Trends and Global Crop Production Since 1980. *Science, 333(6042),* 616-620

[47] Lobiuc A., Vasilache V., Pintilie O., Stoleru T., Burducea M., Oroian M., Zamfirache M. M. (2017). Blue and red LED illumination improves growth and bioactive compounds contents in acyanic and cyanic Ocimum basilicum L. microgreens, *Molecules, 22,* 14

[48] Lubna, F.A., Lewus, D.C., Shelford, T.J., Both, A.-J. (2022). What You May Not Realize about Vertical Farming. *Horticulturae, 8,* 322. https://doi.org/10.3390/horticulturae8040322

[49] López Mora, M.F., Quintero Castellanos, M.F., González Murillo, C.A., Borgovan, C., Salas Sanjuan, M.d.C., Guzmán, M. (2024). Predictive Model to Evaluate Water and Nutrient Uptake in Vertically Grown

Lettuce under Mediterranean Greenhouse Conditions. *Horticulturae, 10,* 117. https://doi.org/10.3390/horticulturae10020117
[50] Magwaza, S.T., Magwaza, L.S., Odindo, A.O., Mditshwa, A., (2020). Hydroponic technology as decentralised system for domestic wastewater treatment and vegetable production in urban agriculture: A review. *Sci. Total Environ., 698*, 134154
[51] Matysiak, B., Kaniszewski, S., Dyśko, J., Kowalczyk, W., Kowalski, A., Grzegorzewska, M. (2021). The Impact of LED Light Spectrum on the Growth, Morphological Traits, and Nutritional Status of 'Elizium' Romaine Lettuce Grown in an Indoor Controlled Environment. *Agriculture, 11,* 1133. https://doi.org/10.3390/agriculture11111133
[52] Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P., and Borin, M. (2017). Hydroponic systems and water management in aquaponics: a review. *Ital. J. Agron. 11*, 1–31. doi: 10.4081/ija.2017.1012
[53] Mir M. S., Naikoo N. B., Kanth R. H., Bahar F.A., Anwar Bhat M., Nazir A., Sheraz Mahdi S., Amin Z., Singh L., Raja W., Saad AA, T. Bhat A, Palmo T., Ahngar T. A., (2022). Vertical farming: The future of agriculture: A review, *The Pharma Innovation Journal, SP-11(2):* 1175-1195
[54] Nájera, C., Gallegos-Cedillo, V.M., Ros, M., Pascual, J.A. (2022). LED Lighting in Vertical Farming Systems Enhances Bioactive Compounds and Productivity of Vegetables Crops. *Biol. Life Sci. Forum, 16,* 24. https://doi.org/10.3390/IECHo2022-12514
[55] Naz S., Haq A.H.M., Rahman M., Khatun M., (2021). An Initiative for Developing Low Cost Hydroponic System. *Haya Saudi J Life Sci.*, ISSN 2415-623X, doi: 10.36348/sjls.2021.v06i01.003
[56] Niu, G., Masabni, J. (2018). Plant Production in Controlled Environments. *Horticulturae, 4,* 28. https://doi.org/10.3390/horticulturae4040028
[57] Nguyen N.T., McInturf S., Mendoza-Cozatl D.G., (2016). Hydroponics: A Versatile System to Study Nutrient Allocation and Plant Responses to Nutrient Availability and Exposure to Toxic Elements. *J Vis Exp., (113)*: 54317. doi: 10.3791/54317
[58] Pantanella, E., Cardarelli, M., Colla, G., Rea, E., & Marcucci, A. (2012). Aquaponics vs. Hydroponics: Production and Quality of Lettuce Crop. *Acta Horticulturae, 947*, 217-223
[59] Park Y., Williams K.A., (2024). Organic hydroponics: A review. *Scientia Horticulturae. Volume 324*, 112604
[60] Patterson, D. T., Westbrook, J. K., Joyce, R. J. V., Lingren, P. D., & Rogasik, J. (2015). Weeds, Insects, and Diseases. *Climatic Change, 43(4),* 711-727
[61] Pennisi, G., Orsini, F., Blasioli, S. et al. (2019). Resource use efficiency of indoor lettuce (Lactuca sativa L.) cultivation as affected by red:blue ratio provided by LED lighting. *Sci Rep 9,* 14127. https://doi.org/10.1038/s41598-019-50783-z
[62] Perez, S.L., Ferro, R.B., Corrêa, B. Casarin R., Correa K., Blanco K.C., Bagnato V.S., (2024). Enhanced vegetable production in hydroponic systems using decontamination of closed circulating fluid. *Sci Rep 14*, 602. https://doi.org/10.1038/s41598-023-50974-9
[63] Phum, Teo E., Chan, K. Y., Mokhtar, S.M., Lee C.L. (2024) Effect of LED Wavelength and Power on the Hydroponic Indoor Vegetable Farming. *Universal Journal of Agricultural Research Vol. 12(1),* pp. 41 – 50, doi: 10.13189/ujar.2024.120105
[64] Promratrak L. (2017). The effect of using LED lighting in the growth of crops hydroponics. *International Journal of Smart Grid and Clean Energy, vol. 6, no. 2,* pp. 133-140, doi: 10.12720/sgce.6.2.133-140
[65] Putra, P. A., and Yuliando, H. (2015). Soilless culture system to support water use efficiency and product quality: a review. *Agric. Agric. Sci. Procedia 3*, 283–288. doi: 10.1016/j.aaspro.2015.01.054
[66] Resh, H. M. (2012). Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. CRC Press
[67] Rezvani, M., Shamshiri, R.R., Hammed, I.A., Abyane, H.Z., Godarzi, M., Momeni, D. (2021). Greenhouse Crop Simulation Models and Microclimate Control Systems, A Review, in Next-Generation Greenhouses for Food Security, Intechopen, ISBN 978-1-83968-076-2, DOI: 10.5772/intechopen.92515
[68] Richa A., Touil S., Fizir M., Martinez V. (2020). Recent advances and perspectives in the treatment of hydroponic wastewater: a review. *Reviews in Environmental Science and Bio/Technology, Volume 19*, 945–966
[69] Sarkar, A., Majumder, M. (2015). Opportunities and Challenges in Sustainability of Vertical Farming: A Review. *Journal of Advanced Agricultural Technologies, 2(3),* 81-86

[70] Sambo P., Nicoletto C., Giro A., Pii Y., Valentinuzzi F., Mimmo T., Lugli P., Orzes G., Mazzetto F., Astolfi S., Terzano R., Cesco S. (2019). Hydroponic Solutions for Soilless Production Systems: Issues and Opportunities in a Smart Agriculture Perspective. *Frontiers in Plant Science, Vol. 10*. ISSN: 1664-462X, doi:10.3389/fpls.2019.00923

[71] Savvas, D. (2003). Hydroponics: A Modern Technology Supporting the Application of Integrated Crop Management in Greenhouse. Food and Agriculture Organization

[72] Sellaro, R., Crepy, M., Trupkin, S.A., Karayekov, E., Buchovsky, A.S., Rossi, C. Casal, J.J. (2010). Cryptochrome as a Sensor of the Blue/Green Ratio of Natural Radiation in Arabidopsis. *Plant Physiology, Vol. 154*, pp. 401–409

[73] Sharma, N., Acharya, S., Kumar, K., Singh, N., Chaurasia, O. P., (2018). Hydroponics as an advanced technique for vegetable production: An overview. *J. Soil Water Conserv. 17*, 364

[74] Smith H. (1982). Light quality, photoperception, and plant strategy. *Annual Review of Plant Physiology 33*, 1882-8

[75] Son J. E., Kim H.J., Ahn T.I., (2020). Plant Factory (Second Edition) An Indoor Vertical Farming System for Efficient Quality Food Production. Chapter 20 – Hydroponic Systems, ISBN 978-0-12-816691-8, https://doi.org/10.1016/B978-0-12-816691-8.00020-0

[76] Stein E.W. (2021). The Transformative Environmental Effects Large-Scale Indoor Farming May Have On Air, Water, and Soil. *Air Soil Water Res., 14*, 1178622121995819

[77] Syed, A.A., Z.A. Khan, S.H. Chattha, I.A. Shaikh, M.N.H.A. Ali, Z.R. Bughio, S.H. Dahri and G.B. Buriro. (2021). Comparative assessment of hydroponic and geoponic cultivation systems for sustainable Spinach cultivation. *Pakistan Journal of Agricultural Research, 34(4):* 678-688

[78] Tharun, R., Padmasine, K.G. (2023). A Review of Grow-light Farming, Hydroponics, Automated Irrigation System, Smart Farming and Spectrum LED. *International Journal of Research Publication and Reviews, Vol 4, no 3,* pp 4706-4711. https://doi.org/10.55248/gengpi.2023.4.3.34385

[79] Tusi, A., Shimazu, T. (2021). Real-time comparison of several transpiration methods for estimating greenhouse ventilation rate via water vapour balance method. *INMATEH-Agricultural Engineering, Volume 78, No. 3,* pp. 81-90, https://doi.org/10.35633/inmateh-63-09

[80] Van Delden, S.H., SharathKumar, M., Butturini, M., Graamans, L.J.A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R.S., Klerkx, L., Kootstra, G., et al., (2021). Current status and future challenges in implementing and upscaling vertical farming systems. *Nat. Food, 2,* 944–956

[81] van Straten, G., van Ooteghem, R., van Henten, E. J., & De Gelder, A. (2011). Optimal Control of Greenhouse Cultivation. CRC Press, ISBN 9781420059618

[82] Van Tuiji E., Hospers G.-J., vn den Berg L. (2018). Opportunities and Challenges of Urban Agriculture for Sustainable City Development. *European Spatial Research Policy, Vol. 25 No. 2*, https://doi.org/10.18778/1231-1952.25.2.01

[83] Velazquez-Gonzalez, R.S., Garcia-Garcia, A.L., Ventura-Zapata, E., Barceinas-Sanchez, J.D.O., Sosa-Savedra, J.C., (2022). A Review on Hydroponics and the Technologies Associated for Medium- and Small-Scale Operations. *Agriculture, 12,* 646. https://doi.org/10.3390/agriculture12050646

[84] Verdoliva S.G., Gwyn-Jones D., Detheridge A., Robson P., (2021). Controlled comparisons between soil and hydroponic systems reveal increased water use efficiency and higher lycopene and β-carotene contents in hydroponically grown tomatoes. *Sci Hortic. 15*, 279: 109896. doi: 10.1016/j.scienta.2021.109896

[85] Xydis G. A., Liaros S., Botsis K., (2017). Energy demand analysis via small scale hydroponic systems in suburban areas – An integrated energy-food nexus solution. *Science of the Total Environment, Volume 593-594*, pp. 610-617

[86] Zhang, X., Cao, D., Wang, M., Cui, G., Shi, Y., Cui, Y. (2022). Nutrient deficiency diagnosis in whole hydroponic lettuce based on random forest, *INMATEH-Agricultural Engineering, Volume 78, No. 3,* pp. 81-90, https://doi.org/10.35633/inmateh-68-08

[87] Zimmermann M., Fisher M., (2020). Impact assessment of water and nutrient reuse in hydroponic systems using Bayesian Belief Networks. *Journal of Water Reuse and Desalination, 10 (4):* 431–442, https://doi.org/10.2166/wrd.2020.026

[88] https://www.trees.com/gardening-and-landscaping/ebb-and-flow-hydroponics (accessed on 03.06.2024)

[89] https://hydroplanner.com/blog/hydroponics-drip-system-EN (accessed on 03.06.2024)

[90] https://www.hydrocentre.com.au/4-x-55w-star-light-t5-fluro-system-with-lamps-110w (accessed on 04.06.2024)

[91] https://www.nosoilsolutions.com/different-types-grow-lights/ (accessed on 04.06.2024)

[92] https://www.sananbiofarm.com/ (accessed on 04.06.2024)

[93] https://marshydro.eu/products/new-fc4000-evo-led-grow-light/ (accessed on 05.06.2024)