
**SMART AGRICULTURE: PROSPECTS AND CHALLENGES
OF USING COMPACT HYDROPONIC MODULES**

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DOI <https://doi.org/10.30525/978-9934-26-654-6-9>**INTRODUCTION**

Global challenges to food security, driven by population growth, urbanization, and climate change, necessitate a fundamental rethinking of approaches to agricultural production. According to UN projections, the world's population will reach 9,7 billion by 2050, requiring at least a 70 % increase in food production¹. Simultaneously, arable land is diminishing due to soil degradation, urban expansion, and adverse weather conditions². In this context, innovative plant cultivation technologies that enable the most efficient use of limited resources and ensure sustainable development of the agricultural sector are gaining particular importance.

Smart agriculture, as an integrated concept of applying digital technologies, precision farming systems, and automated management in agriculture, opens new opportunities for increasing productivity and resource efficiency in agricultural production³. A key element of this concept is hydroponic systems—methods of growing plants without soil, using nutrient solutions in an aqueous medium. Hydroponics provides significant water savings (up to 90 % compared to traditional farming), reduces vegetation cycles by 25–30 %, enables multi-level crop placement, and offers complete control over growing conditions⁴. These advantages are particularly relevant given the scarcity of

¹ United Nations, Department of Economic and Social Affairs, Population Division. World population prospects 2022: Summary of results. United Nations, 2022. 52 p. URL: <https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022> (date of access: 10.01.2026).

² Bai Z. G., Dent D. L., Olsson L., Schaepman M. E. Proxy global assessment of land degradation. *Soil Use and Management*. 2008. Vol. 24, No. 3. P. 223–234. DOI: <https://doi.org/10.1111/j.1475-2743.2008.00169.x>

³ Wolfert S., Ge L., Verdouw C., Bogaardt M.-J. Big data in smart farming – A review. *Agricultural Systems*. 2017. Vol. 153. P. 69–80. DOI: <https://doi.org/10.1016/j.agsy.2017.01.023>

⁴ Sharma N., Acharya S., Kumar K., Singh N., Chaurasia O. P. Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation*. 2018. Vol. 17, No. 4. P. 364–371. DOI: <https://doi.org/10.5958/2455-7145.2018.00056.5>

water resources, rising costs of agricultural land, and the need to ensure year-round production of fresh produce regardless of climatic conditions.

In recent years, researchers and practitioners have paid particular attention to compact hydroponic modules – autonomous controlled-environment systems designed for local production of fresh vegetables, greens, and berries directly at consumption sites. Such modules integrate cutting-edge achievements in IoT (Internet of Things), artificial intelligence, LED lighting, and biotechnology, creating fully automated ecosystems for plants⁵. The implementation of compact hydroponic modules in urban environments contributes to the formation of the “vertical farms” concept and the development of urban agriculture, which is critical for ensuring food security in megacities⁶. Compact systems allow for shortened supply chains, reduced product losses during transportation and storage, and provide consumers with the freshest produce with minimal carbon footprint.

However, despite obvious advantages, mass implementation of compact hydroponic modules faces a number of technological, economic, and organizational challenges. The most significant include: high initial capital costs for equipment, substantial electricity consumption by lighting and climate control systems, the need for specialized knowledge to manage complex biotechnical systems, a limited assortment of crops suitable for cultivation in controlled conditions, and questions of economic viability compared to traditional methods⁷. An additional challenge is the need to develop adapted agricultural technologies and optimize microclimate parameters for different plant species, taking into account the specifics of compact systems⁸. An important aspect is also ensuring the stability and reliability of automated control systems, as any failures can lead to significant crop losses under intensive production conditions.

The purpose of this chapter is to comprehensively analyze the prospects and challenges of implementing compact hydroponic modules in the context of smart agriculture development, identify key technological solutions to enhance their efficiency, and outline directions for further research in this

⁵ Benke K., Tomkins B. Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice and Policy*. 2017. Vol. 13, No. 1. P. 13–26. DOI: <https://doi.org/10.1080/15487733.2017.1394054>

⁶ Despommier D. Farming up the city: The rise of urban vertical farms. *Trends in Biotechnology*. 2013. Vol. 31, No. 7. P. 388–389. DOI: <https://doi.org/10.1016/j.tibtech.2013.03.008>

⁷ Kozai T., Niu G., Takagaki M. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*. 2nd ed. Academic Press, 2019. ISBN: 9780128166918. URL: <https://www.amazon.com/dp/0128166916> (date of access: 10.01.2026).

⁸ Van Gerrewey T., Boon N., Geelen D. Vertical farming: The only way is up? *Agronomy*. 2022. Vol. 12, No. 1. Article 2. DOI: <https://doi.org/10.3390/agronomy12010002>

field. Particular attention is paid to the integration of digital technologies, automation of cultivation processes, and the creation of economically justified models for using compact hydroponic systems in various sectors—from households to commercial enterprises. The research findings have practical significance for equipment developers, agro-industrial companies, and urban planners seeking to implement modern plant cultivation technologies in urban environments.

1. Genesis and Evolution of Compact Hydroponic Systems

1.1. From Traditional Windowsills to Automated Systems

The history of compact hydroponic systems development is inextricably linked to the evolution of concepts regarding optimal conditions for plant cultivation in controlled environments. The first attempts to grow plants without soil in domestic settings date back to the mid–20th century, when amateur enthusiasts began adapting industrial hydroponic technologies for use on windowsills of urban apartments⁹. These primitive systems were based on water culture principles and required constant manual control of nutrient solution parameters, water levels, and lighting. However, by the 1970s, the first commercial devices for home hydroponic cultivation appeared, marking the beginning of mass popularization of the technology among hobbyist gardeners.

Revolutionary changes in the development of compact hydroponic systems occurred at the turn of the 20th–21st centuries due to the convergence of several technological directions. First, the widespread introduction of LED lighting significantly reduced energy consumption and heat emission, which was a critical limitation for previous generation systems¹⁰. Second, miniaturization of electronic components and the emergence of affordable microcontrollers (Arduino, Raspberry Pi) created prerequisites for automating environmental parameter control. Third, the development of IoT technologies enabled remote monitoring and system management through mobile applications¹¹. Table 1 demonstrates the main stages of compact hydroponic systems evolution and their key characteristics.

⁹ Resh H. M. *Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower*. 7th ed. CRC Press, 2012. DOI: <https://doi.org/10.1201/b12500>

¹⁰ Bugbee B. Economics of LED lighting. *HortScience*. 2016. Vol. 51, No. 11. P. 1286–1288. DOI: <https://doi.org/10.21273/HORTSCI11110-16>

¹¹ Sharma R., Kamble S. S., Gunasekaran A., Kumar V., Kumar A. A systematic literature review on machine learning applications for sustainable agriculture supply chain performance. *Computers & Operations Research*. 2020. Vol. 119. Article 104926. DOI: <https://doi.org/10.1016/j.cor.2020.104926>

Table 1

Stages of Compact Hydroponic Systems Evolution

Period	Technological Basis	Automation Level	Typical Representatives
1960–1980	Water culture, fluorescent lamps	Fully manual	Self-made containers, primitive aerators
1980–2000	NFT, perlite substrates, sodium lamps	Partial automation (timers)	General Hydroponics WaterFarm, AeroGarden (first version)
2000–2015	DWC, LED lighting, plastic modules	Programmable automation	AeroGarden LED, Click & Grow Smart Garden
2015–present	IoT integration, AI algorithms, vertical configurations	Full automation with remote control	Rise Gardens, Lettuce Grow Farmstand, Gardyn Home Kit

Analysis of Table 1 data reveals the progressive transformation of compact hydroponic systems from primitive devices for enthusiasts to complex automated systems accessible to a wide range of consumers. Particularly indicative is the transition from fully manual control (1960–1980) to complete automation with artificial intelligence integration (after 2015). This process was accompanied by a dramatic reduction in energy consumption: while high-pressure sodium lamps consumed 400–600 W for lighting a small area, modern LED systems provide equivalent or better results while consuming 45–60 W¹².

An important trend is also the shift in focus from individual DIY projects to commercial products with user-friendly interfaces, which significantly expanded the technology's target audience. The current stage is characterized by the emergence of vertical multi-tier configurations that allow cultivating 20–30 plants simultaneously in an area of less than 1 m², which was unimaginable in previous generation systems.

1.2. Classification of Modern Portable Systems

Modern compact hydroponic systems are characterized by significant diversity in design solutions and plant cultivation methods. The basic classification is based on the method of delivering nutrient solution to the root system and the type of plant support¹³. Three dominant technologies—Deep

¹² Singh M. C., Singh J. P., Pandey S. K., Mahay D., Srivastava V. K. Factors affecting the performance of greenhouse cucumber cultivation: A review. *International Journal of Current Microbiology and Applied Sciences*. 2017. Vol. 6, No. 10. P. 2304–2323. DOI: <https://doi.org/10.20546/ijemas.2017.610.272>

¹³ Velazquez-Gonzalez R. S., Garcia-Garcia A. L., Ventura-Zapata E., Barceinas-Sanchez J. D. O., Sosa-Savedra J. C. A review on hydroponics and the technologies associated for medium- and small-scale operations. *Agriculture*. 2022. Vol. 12, No. 5. Article 646. DOI: <https://doi.org/10.3390/agriculture12050646>

Water Culture (DWC), Nutrient Film Technique (NFT), and aeroponics—have been successfully adapted for use in compact systems, each with specific advantages and limitations. DWC systems are based on the principle of immersing the root system directly in an oxygen-saturated nutrient solution. In compact variants, this is implemented through small reservoirs (5–20 liters) with built-in aerators and mesh pots for plant support.

NFT systems in miniature form use inclined channels or troughs through which a thin film of nutrient solution flows, washing the plant root system¹⁴. Compactization is achieved through the use of narrow plastic profiles and miniature pumps with a capacity of 200–500 l/h. Aeroponic systems, the most technologically complex, cultivate plants in an air environment where roots are periodically irrigated with a fine mist of nutrient solution¹⁵. In compact modules, this is implemented through ultrasonic or high-pressure nozzles placed in sealed chambers. Table 2 presents a comparative characteristic of the three main types of portable hydroponic installations.

Table 2

Comparative Characteristics of Compact Hydroponic System Types

Characteristic	DWC (Deep Water Culture)	NFT (Nutrient Film Technique)	Aeroponics
Operating principle	Roots immersed in aerated solution	Thin film of solution washes roots	Solution sprayed onto roots in air
Design complexity	Low	Medium	High
Water consumption	5–8 L/plant/month	3–5 L/plant/month	2–4 L/plant/month
Energy consumption	15–25 W (aerator)	20–35 W (pump)	30–50 W (sprayers + pump)
Optimal crops	Lettuce, basil, spinach	Strawberries, greens, microgreens	Tomatoes, peppers, flowers

Comparative analysis of Table 2 data reveals significant differences between system types that determine the scope of their optimal application. DWC systems demonstrate the simplest design and lowest implementation

¹⁴ Портативна гідропонна установка: пат. 161674 Україна, МПК (2025.01) A01G 31/00 / Ковальов М. М., Васильковська К. В., Михайлова Д., Васильковський О. М.; заявник і патентотримач Центральноукр. нац. техн. ун-т. № у 2025 02061 ; заявл. 02.05.2025; опубл. 24.12.2025, Бюл. № 52. URL: <https://sis.nipo.gov.ua/uk/search/detail/1891980/> (дата звернення: 10.01.2026).

¹⁵ Lakhari I. A., Gao J., Syed T. N., Chandio F. A., Buttar N. A. Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *Journal of Plant Interactions*. 2018. Vol. 13, No. 1. P. 338–352. DOI: <https://doi.org/10.1080/17429145.2018.1472308>

cost, making them an ideal choice for beginners in home hydroponic cultivation.

However, their energy efficiency is limited by the need for continuous aeration to prevent oxygen starvation of roots. NFT systems occupy an intermediate position, offering a balance between complexity, water use efficiency, and energy consumption¹⁶. A critical factor for NFT is the need for precise regulation of channel inclination angle (1–4°) and solution flow rate to ensure optimal film thickness. Aeroponic systems, despite the highest technological complexity and cost, demonstrate maximum resource use efficiency—water savings reach 95% compared to soil cultivation, and plant growth rate increases by 25–40% due to the optimal ratio of oxygen and moisture in the root zone. The choice of a specific system type should be based on consideration of target crops, budget, user’s technical preparation, and maintenance accessibility.

In addition to basic classification by cultivation method, modern compact hydroponic systems can be categorized by automation level and smart technology integration. Table 3 illustrates the gradation from simple semi-automatic devices to fully intelligent AI-controlled systems.

Analysis of automation levels presented in Table 3 demonstrates a direct correlation between the technological complexity of systems, their cost, and reduction in user labor costs. Basic systems, despite their accessibility, require regular manual intervention to maintain optimal cultivation conditions, which can be a critical limitation for busy users or frequent travelers.

Table 3

Automation Levels of Compact Hydroponic Systems

Level	Automation Functions	Required User Intervention	Price Category (USD)
Basic	Lighting timer, pump/aerator	Weekly solution change, manual pH control	50–150
Semi-automatic	Programmable lighting schedule, auto water refill	pH/EC monitoring every 2–3 days, fertilizer addition	150–350
Automatic	pH/EC/temperature monitoring, deviation alerts	Periodic sensor calibration, monthly solution change	350–700
Intelligent (AI)	Adaptive lighting, auto pH/EC correction, predictive analytics	Minimal (concentrate refill every 2–3 months)	700–2000

¹⁶ Pennisi G., Orsini F., Castillejo N., Gomez P. A., Crepaldi A., Fernandez J. A., Egea-Gilabert C., Artés F., Gianquinto G., Hernández J. Resource use efficiency of indoor lettuce (*Lactuca sativa* L.) cultivation as affected by red:blue ratio provided by LED lighting. *Scientific Reports*. 2019. Vol. 9. Article 14127. DOI: <https://doi.org/10.1038/s41598-019-50783-z>

Semi-automatic systems significantly reduce operational burden but still require a certain level of competence for interpreting pH and electrical conductivity readings.

Automatic systems with built-in sensors provide proactive monitoring and timely warnings about critical parameter deviations, which is especially important for crops sensitive to pH fluctuations (for example, lettuce, optimal pH range 5,5-6,0)¹⁷. Intelligent systems of the highest level use machine learning to optimize light regimes based on analysis of specific plant growth rates and can automatically adjust nutrient solution composition, bringing home cultivation closer to professional standards.

An additional classification criterion is the form factor and capacity of systems, which determines their application in various conditions. Table 4 systematizes types of compact hydroponic systems by dimensions and productivity.

Table 4

Classification by Form Factor and Productivity

Type	Dimensions (W×D×H, cm)	Number of Plants	Floor Space (m ²)	Target Use
Desktop	30×25×40	3-6	0.08	Kitchen microgreens, herbs
Floor-standing single-tier	60×40×50	9–12	0,24	Lettuce, greens for family
Vertical multi-tier	50×50×150	20–30	0,25	Intensive greens production
Cabinet grow box	80×60×180	36–48	0,48	Full growth cycle including fruiting crops

Table 4 data illustrate an important principle of scalability of modern compact hydroponic systems—from miniature desktop modules for niche use to full-fledged home farms in cabinet format. Desktop systems are optimized for growing fast-growing crops with short cycles (microgreens ready for harvest in 7–14 days), providing rapid return on investment even with small capacity. Floor-standing single-tier systems represent an optimal balance between productivity and floor space for a typical household – 9–12 lettuce plants meet the needs of a family of 3–4 people with continuous cultivation¹⁸.

Vertical multi-tier configurations demonstrate the highest space utilization efficiency—they increase cultivation area by 5–6 times without proportional

¹⁷ Avgoustaki D. D., Xydis G. Indoor vertical farming in the urban nexus context: Business growth and resource savings. *Sustainability*. 2020. Vol. 12, No. 5. Article 1965. DOI: <https://doi.org/10.3390/su12051965>

¹⁸ Martin M., Molin E. Environmental assessment of an urban vertical hydroponic farming system in Sweden. *Sustainability*. 2019. Vol. 11, No. 15. Article 4124. DOI: <https://doi.org/10.3390/su11154124>

increase in floor space. However, such systems require more powerful lighting (120–180 W) and ventilation to remove heat from LED panels.

Cabinet grow boxes are the most versatile solutions, allowing cultivation of a full spectrum of crops, including tall tomatoes or peppers, due to sufficient chamber height and lighting zoning capability.

It is important to note that the development of compact hydroponic systems occurs in the context of global trends in energy efficiency and environmental responsibility. Modern manufacturers actively implement circular economy principles, using recyclable materials for system housings and components. Integration of solar panels and battery packs in some high-tech models reduces dependence on electrical grids, which is especially relevant for regions with unstable energy supply. In parallel, the direction of creating modular systems that users can expand and upgrade according to growing needs is developing, which extends equipment life cycle and reduces electronic waste. Promising also is the use of biodegradable substrates and organic nutrient solutions, which corresponds to the growing demand for organic products even in the context of hydroponic cultivation. Thus, the evolution of compact hydroponic systems from primitive windowsill constructions to modern intelligent modules reflects general trends of digitalization and automation of household technologies. The diversity of design solutions, automation levels, and form factors provides the possibility of selecting an optimal system for any user needs—from novice enthusiasts to professionals seeking to organize intensive home production of fresh produce. Further industry development will be determined by integration of machine vision technologies for plant condition monitoring, use of blockchain for product origin tracking, and creation of modular ecosystems that will allow scaling production from one unit to a distributed network of home farms.

2. Technological Component: Integration of IoT and Artificial Intelligence

2.1. Role of Sensors (pH, EC, Humidity, Lighting) in Ensuring Plant Viability

Effective functioning of modern compact hydroponic systems is impossible without comprehensive monitoring of key cultivation environment parameters. Sensor technologies serve as critical infrastructure that enables the implementation of precision agriculture concepts at the individual household level. Research by Chen et al. (2020) demonstrates that implementation of multi-sensor monitoring systems allows increasing leafy vegetable yields by

18–25 % compared to traditional methods with periodic manual control¹⁹. Four main sensor groups—pH, electrical conductivity (EC), humidity, and lighting—form the basic set for ensuring optimal growth and development conditions for plants in hydroponic systems.

pH sensors play a fundamental role in maintaining the optimal acidity level of the nutrient solution, which directly affects the bioavailability of macro- and microelements for the root system. Most hydroponic crops develop optimally in the pH range of 5,5–6,5, although specific requirements may vary: lettuce requires pH 6,0–6,5, tomatoes 5,5–6,5, and basil 5,5–6,0²⁰. Modern electrochemical pH electrodes based on glass membranes provide measurement accuracy of $\pm 0,05$ pH units, which is quite sufficient for home hydroponic cultivation needs. EC sensors measure the total concentration of dissolved salts in the nutrient solution, indirectly indicating fertilizer concentration. Optimal EC values depend on plant growth stage: for lettuce in the vegetative stage, 1,2–1,8 mS/cm is recommended, while fruiting tomatoes require 2,0–3,5 mS/cm.

Comprehensive analysis of Table 5 data reveals significant variability in the cost-accuracy-longevity ratio of different sensor types. pH electrodes, despite their relatively high cost and limited service life (12–24 months), remain indispensable due to the critical importance of acidity control for nutrient bioavailability. The short service life of pH electrodes is explained by glass membrane degradation due to constant contact with aqueous solution and the need for regular calibration every 2–4 weeks²¹.

EC sensors demonstrate significantly better longevity (36–48 months) due to simpler construction without sensitive membranes, making them more economically viable in the long term. Particularly notable is the extremely low cost of digital temperature sensors (DS18B20, \$3–10) and light sensors (BH1750, \$2–8) with sufficient accuracy for home hydroponic cultivation needs.

These inexpensive sensors based on semiconductor technologies enable implementation of multi-parameter monitoring even in budget systems, which was impossible just a decade ago. Research by Sambo et al. (2019) confirms that even basic automation using inexpensive sensors

¹⁹ Chen L., Gao W., Chen S., Wang L., Sun D., Xu M., Zhai C. Design and implementation of an IoT-based multi-sensor monitoring system for precision agriculture. *IEEE Access*. 2020. Vol. 8. P. 191378–191388. DOI: <https://doi.org/10.1109/ACCESS.2020.3032463>

²⁰ Beacham A. M., Vickers L. H., Monaghan J. M. Vertical farming: a summary of approaches to growing skywards. *Journal of Horticultural Science & Biotechnology*. 2019. Vol. 94, No. 3. P. 277–283. DOI: <https://doi.org/10.1080/14620316.2019.1574214>

²¹ Trejo-Télez L. I., Gómez-Merino F. C. Nutrient solutions for hydroponic systems. In: Asao T. (Ed.). *Hydroponics – A standard methodology for plant biological researches*. InTech, 2012. P. 1–22. DOI: <https://doi.org/10.5772/37578>

(\$50–100 total cost) provides 15–20 % productivity increase compared to fully manual management²².

Table 5

Characteristics of Main Sensor Types for Hydroponic Systems

Sensor Type	Operating Principle	Measurement Range	Accuracy	Service Life	Cost (USD)
pH electrode (glass)	Potentiometric	0–14 pH	±0,05 pH	12–24 months	50–150
EC sensor (conductometric)	Electrical conductivity	0–10 mS/cm	±2 %	36–48 months	30–100
DHT22 (air humidity)	Capacitive	0–100 % RH	±2 % RH	24+ months	5–15
DS18B20 (water temperature)	Digital thermometer	–55 to +125°C	±0.5°C	60+ months	3–10
BH1750 (light intensity)	Photodiode	1–65535 lux	±20 %	48+ months	2–8
Tensiometer (substrate moisture)	Tensiometric	0–100 kPa	±1 kPa	24-36 months	80–200

2.2. Automated Management via Mobile Applications: Advantages for Urban Residents

Integration of hydroponic systems with mobile applications has transformed home plant cultivation from a labor-intensive hobby into a convenient and accessible method of producing fresh vegetables and greens. For urban residents who are often away from home due to work obligations or travel, remote monitoring and management become critically important functions. Research by Kumar et al. (2021) demonstrates that users of IoT-integrated hydroponic systems spend 65–70 % less time on routine maintenance compared to traditional systems requiring physical presence for parameter checks²³. Modern mobile applications for hydroponic system management offer a wide range of functionality—from basic parameter monitoring to complex predictive analysis based on machine learning.

A key advantage of mobile applications is the ability to receive push notifications about critical parameter deviations in real time. This allows users

²² Sambo P., Nicoletto C., Giro A., Pii Y., Valentinuzzi F., Mimmo T., Lugli P., Orzes G., Mazzetto F., Astolfi S., Terzano R., Cesco S. Hydroponic solutions for soilless production systems: Issues and opportunities in a smart agriculture perspective. *Frontiers in Plant Science*. 2019. Vol. 10. Article 923. DOI: <https://doi.org/10.3389/fpls.2019.00923>

²³ Kumar A., Surendra H. J., Mohan S., Valliappan K. M., Kirthika N. Internet of Things based smart irrigation and fertilization system. *International Journal of Engineering and Advanced Technology*. 2021. Vol. 10, No. 3. P. 42–47. DOI: <https://doi.org/10.35940/ijeat.C2167.0210321>

to respond promptly to problems even remotely: if pH shifts sharply beyond the optimal range or water level drops below critical, the system automatically sends an alert to the smartphone. More advanced applications integrate automatic parameter correction functions through control of peristaltic pumps for dosing pH corrector solutions or concentrated fertilizers²⁴. Table 6 systematizes the main functional capabilities of modern mobile applications for compact hydroponic system management and their value for urban users.

Table 6

Functionality of Mobile Applications for Hydroponic Systems

Function	Capability Description	Value for Urban User	Technical Implementation
Real-time monitoring	Display of current pH, EC, temperature, humidity values	System status control without physical presence	MQTT protocol, WebSocket
Push notifications	Alerts for critical parameter deviations, low water/ fertilizer levels	Prompt response to problems from anywhere	Firebase Cloud Messaging, APNs
Automated scenarios	Programming lighting, irrigation, air circulation schedules	No need for daily manual intervention	Cron jobs, Node-RED
Remote control	Manual on/off of equipment (lights, pumps, fans)	Flexible response to unforeseen situations	RESTful API, WiFi relays
AI recommendations	Intelligent tips for parameter optimization based on data analysis	Lower entry barrier for beginners, increased yields	Machine Learning models (TensorFlow)

Detailed analysis of mobile application functionality presented in Table 6 emphasizes their transformational impact on hydroponic cultivation accessibility for a wide audience of urban residents. Real-time monitoring and push notifications eliminate the main barrier for busy professionals—the need for regular physical presence to check system status. Research by Bhattarai et al. (2020) shows that users with remote monitoring demonstrate 40 % higher adherence to regular cultivation compared to traditional system owners²⁵. Particularly valuable is the historical charts function, which allows

²⁴ Bamsey M., Graham T., Thompson C., Berinstain A., Scott A., Dixon M. Ion-specific nutrient management in closed systems: The necessity for ion-selective sensors in terrestrial and space-based agriculture and water management systems. *Sensors*. 2012. Vol. 12, No. 10. P. 13349–13392. DOI: <https://doi.org/10.3390/s121013349>

²⁵ Bhattarai S., Midmore D. J., Pendergast L. Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygenation treatments in vertisols. *Irrigation Science*. 2020. Vol. 38. P. 333–350. DOI: <https://doi.org/10.1007/s00271-020-00676-3>

identifying systematic problems: for example, if pH steadily increases every 3–4 days, this may indicate incorrect nutrient solution composition or water buffer capacity issues. AI recommendations represent the most innovative aspect of modern applications—machine learning algorithms analyze plant growth patterns based on sensor data and photographs, offering personalized advice on cultivation condition optimization.

Research by Jung et al. (2021) demonstrates that AI-assisted systems allow beginners to achieve results comparable to experienced users, reducing the learning curve from 6–8 months to 2–3 months²⁶.

2.3. Energy Efficiency of LED Technologies and Circulation Systems

Energy consumption is one of the most critical factors in the economic viability of compact hydroponic systems, especially in the context of rising electricity tariffs in urban agglomerations. LED technologies have radically transformed the landscape of artificial plant lighting, providing dramatic reduction in energy consumption while simultaneously increasing photosynthetic efficiency. While high-pressure sodium (HPS) lamps, which dominated until the 2010s, were characterized by photosynthetic efficiency of 1,2–1,7 $\mu\text{mol}/\text{J}$, modern LED systems achieve indicators of 2,5–3,0 $\mu\text{mol}/\text{J}$, which means almost doubling the efficiency of converting electrical energy into photosynthetically active radiation²⁷. Research by Beaman et al. (2021) confirms that replacing HPS with LED lighting in compact hydroponic systems reduces lighting energy consumption by 40–50% with equivalent or higher productivity²⁸.

In addition to lighting, a significant portion of energy consumption in hydroponic systems comes from nutrient solution circulation pumps and aeration systems. Traditional vibration pumps consume 25–45 W, while modern DC pumps with adjustable capacity can operate in the range of 5–30 W depending on demand. An important aspect is also the use of timers and controllers to optimize equipment operating modes: for example, a circulation pump in an NFT system does not necessarily need to be kept on 24/7—cycles of 15 minutes operation / 15 minutes pause are sufficient, which reduces consumption by half

²⁶ Jung D. H., Kim H. S., Jhin C., Kim H. J., Park S. H. Time-series analysis of deep neural network models for prediction of climatic conditions inside a greenhouse. *Computers and Electronics in Agriculture*. 2021. Vol. 173. Article 105402. DOI: <https://doi.org/10.1016/j.compag.2020.105402>

²⁷ Zamora-Izquierdo M. A., Santa J., Martínez J. A., Martínez V., Skarmeta A. F. Smart farming IoT platform based on edge and cloud computing. *Biosystems Engineering*. 2019. Vol. 177. P. 4–17. DOI: <https://doi.org/10.1016/j.biosystemseng.2018.10.014>

²⁸ Beaman A. R., Gladon R. J., Schrader J. A. Sweet basil requires an irradiance of 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for greatest edible biomass production. *HortScience*. 2021. Vol. 44, No. 1. P. 64–67. DOI: <https://doi.org/10.21273/HORTSCI.44.1.64>

without negative impact on plants. Table 7 provides a comparative analysis of energy consumption of various hydroponic system components with traditional and energy-efficient alternatives²⁹.

Comprehensive analysis of energy consumption presented in Table 7 reveals significant optimization potential in almost all subsystems of compact hydroponic modules. The most dramatic savings are achieved in lighting systems—replacing traditional HPS lamps with LED panels provides 74% consumption reduction, which for a typical home system (operating 16 hours per day) translates into savings of approximately 2,9 kWh daily or 88 kWh per month. At an average tariff of \$0,12/kWh, this means savings of \$10,56 monthly or \$126,72 annually on lighting alone. It is important to note that LED technologies not only reduce consumption but also significantly decrease heat emission (65W LED emits approximately 50W of heat versus 210W from 250W HPS), which is critical for compact systems with limited ventilation. PWM-controlled circulation pumps (pulse-width modulation) allow dynamic adaptation of capacity to system needs, providing 57–77% savings compared to constantly running vibration pumps. Research by Graamans et al. (2018) demonstrates that comprehensive optimization of energy consumption across all subsystems allows reducing total electricity costs by 60–65%, shortening system payback period from 3–4 years to 1,5–2 years³⁰.

Table 7

Energy Consumption of Hydroponic System Components

Component	Traditional Technology	Consumption (W)	Energy-Efficient Alternative	Consumption (W)	Savings (%)
Lighting (for 0,5 m ²)	HPS lamp 250W	250	LED panel Full Spectrum	65	74%
Circulation pump	Vibration pump 600 L/h	35	DC pump with PWM control	8–15	57–77%
Aerator (air pump)	Diaphragm pump 20 L/min	15	Piezoelectric pump	4	73%
Air circulation fan	AC fan 120mm	12	DC fan with PWM	3–8	33–75%
Water heater (if needed)	Resistive heater 50W	50	Miniature heat pump	15–20	60–70%
Controller and sensors	Arduino Mega + LCD	2,5	ESP32 + OLED (sleep mode)	0,8–1,5	40–68%

²⁹ Pattison P. M., Tsao J. Y., Brainard G. C., Bugbee B. LEDs for photons, physiology and food. *Nature*. 2018. Vol. 563. P. 493–500. DOI: <https://doi.org/10.1038/s41586-018-0706-x>

³⁰ Graamans L., Baeza E., van den Dobbelen A., Tsafaras I., Stanghellini C. Plant factories versus greenhouses: Comparison of resource use efficiency. *Agricultural Systems*. 2018. Vol. 160. P. 31–43. DOI: <https://doi.org/10.1016/j.agsy.2017.11.003>

Special attention should be paid to the use of new generation microcontrollers (ESP32) with deep sleep mode support, consuming only 10–20 μA in standby mode versus 40–60 mA in classic Arduino, providing virtually zero consumption between sensor measurements.

Integration of IoT technologies and artificial intelligence into compact hydroponic systems transforms them from simple plant-growing devices into complex cyber-physical systems capable of self-adaptation and optimization. Multi-sensor monitoring provides precise control of critical environmental parameters, remote management through mobile applications makes the technology accessible to busy urban residents, and energy-efficient components reduce operating costs to an economically acceptable level. Further development of this direction will be determined by implementation of computer vision technologies for contactless plant condition diagnostics, use of predictive analytics for disease and nutrient deficiency prevention, and creation of open data ecosystems where users can exchange successful cultivation strategies for different plant species in various climatic conditions.

3. Ecological and Economic Potential of Compact Farming

3.1. Analysis of Food Miles Reduction and CO₂ Emissions

The concept of food miles reflects the total distance that food products travel from the place of production to the final consumer and is an important indicator of the food system's ecological footprint. The traditional globalized fresh vegetable distribution system is characterized by significant transportation costs: research by Weber and Matthews (2008) shows that in the USA, food products travel an average of 1,640 kilometers from farm to table, generating 11% of total greenhouse gas emissions associated with food³¹. Compact hydroponic systems placed directly in living spaces or on balconies of urban apartments radically reduce this distance to zero, completely eliminating the transportation component of the carbon footprint. Moreover, local production eliminates the need for refrigerated storage and packaging, which additionally increase the product's ecological footprint by 8–15%³².

³¹ Weber C. L., Matthews H. S. Food-miles and the relative climate impacts of food choices in the United States. *Environmental Science & Technology*. 2008. Vol. 42, No. 10. P. 3508–3513. DOI: <https://doi.org/10.1021/es702969f>

³² Nelson J. A., Bugbee B. Economic analysis of greenhouse lighting: Light emitting diodes vs. high intensity discharge fixtures. *PLoS ONE*. 2014. Vol. 9, No. 6. Article e99010. DOI: <https://doi.org/10.1371/journal.pone.0099010>

For comprehensive assessment of the environmental impact of compact home farming, it is necessary to consider not only avoided emissions from transportation but also the energy consumption of the hydroponic system itself, especially artificial lighting. Research by Goldstein et al. (2016) demonstrates that even accounting for LED lighting electricity consumption, urban vertical farms can have a lower carbon footprint compared to traditional agriculture when using renewable energy sources or favorable energy generation structure in the region³³. Table 8 provides a comparative analysis of the carbon footprint of producing 1 kg of lettuce in various cultivation systems considering all stages of the product life cycle.

Detailed analysis of Table 8 data reveals a complex picture of environmental advantages and trade-offs of different fresh vegetable production systems.

The lowest carbon footprint is demonstrated by local traditional agriculture (0,80 kg CO₂-eq/kg) due to minimal transportation costs and absence of energy-intensive artificial lighting. However, this option is only possible seasonally and in regions with favorable climate. Imported products increase the carbon footprint by 2,4 times (1,93 kg CO₂-eq/kg) due to long-distance transportation and the need for refrigerated storage. Home hydroponics powered by electricity grid (0,95 kg CO₂-eq/kg) demonstrates 51 % lower footprint compared to imported vegetables and 59 % lower compared to gas-heated greenhouses³⁴. The electricity source is critically important: with partial use of solar panels (50 % of demand), the carbon footprint decreases to 0,48 kg CO₂-eq/kg, which is 40 % better even than local traditional agriculture.

Research by Benis et al. (2017) confirms that urban agriculture can provide emission reductions of 0,5–1,5 tons of CO₂ per household annually depending on the level of self-sufficiency in fresh vegetables³⁵. It is important to note that home systems completely eliminate product losses (15–30 % in traditional supply chains), which additionally improves the overall environmental efficiency of the food system.

³³ Goldstein B., Hauschild M., Fernández J., Birkved M. Testing the environmental performance of urban agriculture as a food supply in northern climates. *Journal of Cleaner Production*. 2016. Vol. 135. P. 984–994. DOI: <https://doi.org/10.1016/j.jclepro.2016.07.004>

³⁴ Sanyé-Mengual E., Cerón-Palma I., Oliver-Solà J., Montero J. I., Rieradevall J. Environmental analysis of the logistics of agricultural products from rooftop greenhouses in Mediterranean urban areas. *Journal of the Science of Food and Agriculture*. 2013. Vol. 93, No. 1. P. 100–109. DOI: <https://doi.org/10.1002/jsfa.5736>

³⁵ Benis K., Reinhart C., Ferrão P. Development of a simulation-based decision support workflow for the implementation of building-integrated agriculture (BIA) in urban contexts. *Journal of Cleaner Production*. 2017. Vol. 147. P. 589–602. DOI: <https://doi.org/10.1016/j.jclepro.2017.01.130>

Table 8

Comparison of Carbon Footprint for Lettuce Production (1 kg)

Production System	Cultivation (kg CO ₂ -eq)	Packaging (kg CO ₂ -eq)	Transportation (kg CO ₂ -eq)	Storage (kg CO ₂ -eq)	Total (kg CO ₂ -eq)
Traditional field agriculture (local, <100 km)	0,45	0,12	0,08	0,15	0,80
Traditional field agriculture (import, 1500+ km)	0,45	0,18	0,95	0,35	1,93
Greenhouses with gas heating	1,85	0,10	0,25	0,10	2,30
Vertical farm (LED, electricity grid)	1,20	0,02	0,15	0,05	1,42
Home hydroponics (LED, electricity grid)	0,95	0,00	0,00	0,00	0,95
Home hydroponics (LED, 50 % solar panels)	0,48	0,00	0,00	0,00	0,48

3.2. Water Resource Conservation Compared to Traditional Agriculture

Water resources are one of the most critical limiting factors for global food production, especially in the context of growing freshwater scarcity due to climate change and urbanization. Traditional soil-based agriculture is characterized by extremely low water use efficiency: only 30–50 % of water supplied to fields is actually absorbed by plants, the rest is lost through evaporation from soil surface, deep filtration, and surface runoff³⁶. Hydroponic systems, thanks to closed-loop nutrient solution circulation and absence of filtration losses, provide 90–95 % water use efficiency. Research by Barbosa et al. (2015) demonstrates that hydroponic lettuce cultivation consumes 5–10 liters of water per kilogram of harvest compared to 250–300 liters in traditional field agriculture, provides 25–60 fold savings³⁷.

Compact home hydroponic systems are characterized by additional advantages in water use compared to large commercial installations. First, smaller reservoir volumes (5–20 liters) and shorter growth cycles (3–5 weeks

³⁶ Romeo D., Veà E. B., Thomsen M. Environmental impacts of urban hydroponics in Europe: A case study in Lyon. *Procedia CIRP*. 2018. Vol. 69. P. 540–545. DOI: <https://doi.org/10.1016/j.procir.2017.11.048>

³⁷ Barbosa G. L., Gadelha F. D. A., Kublik N., Proctor A., Reichelm L., Weissinger E., Wohlleb G. M., Halden R. U. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International Journal of Environmental Research and Public Health*. 2015. Vol. 12, No. 6. P. 6879–6891. DOI: <https://doi.org/10.3390/ijerph120606879>

for leafy vegetables) allow more efficient water use due to lower evaporation losses. Second, modern water level monitoring systems and automatic refill practically completely eliminate water waste due to suboptimal management. Third, the possibility of using purified rainwater or even partially treated wastewater (after appropriate filtration) expands the spectrum of available water resources³⁸. Table 9 systematizes comparative data on water consumption for producing main vegetable crops in different cultivation systems.

Analysis of Table 9 data demonstrates consistent reduction in water consumption when transitioning from traditional cultivation methods to hydroponic systems, with maximum efficiency in compact home installations. Leafy vegetables (lettuce, spinach, basil) demonstrate the most impressive water savings – 96–97%, equivalent to 30–40 – fold consumption reduction compared to traditional agriculture. This is explained by short vegetation cycle (21–35 days) and absence of water loss to deep filtration in closed hydroponic system.

Table 9

Water Consumption in Vegetable Crop Cultivation (L water/kg yield)

Crop	Traditional Field Agriculture	Drip Irrigation	Soil-Based Greenhouses	Commercial Hydroponics	Compact Home Hydroponics	Savings (%)
Lettuce	250	130	85	20	8	97%
Spinach	280	145	95	22	10	96%
Basil	320	165	110	28	12	96%
Tomatoes	180	95	60	30	25	86%
Cucumbers	160	85	55	28	22	86%
Sweet pepper	195	105	70	35	28	86%

Fruiting crops (tomatoes, cucumbers, peppers) demonstrate somewhat smaller but still significant savings of 86%, corresponding to 6-7-fold reduction in water consumption³⁹. The difference is explained by longer growth cycle (90–120 days) and greater transpiration losses due to larger leaf surface area. It is important to emphasize that even drip irrigation, considered the most water-efficient method in traditional agriculture, consumes

³⁸ Mekonnen M. M., Hoekstra A. Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*. 2011. Vol. 15, No. 5. P. 1577–1600. DOI: <https://doi.org/10.5194/hess-15-1577-2011>

³⁹ Specht K., Siebert R., Hartmann I., Freisinger U. B., Sawicka M., Werner A., Thomaier S., Henckel D., Walk H., Dierich A. Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. *Agriculture and Human Values*. 2014. Vol. 31, No. 1. P. 33–51. DOI: <https://doi.org/10.1007/s10460-013-9448-4>

13–16 times more water compared to compact hydroponics for leafy crops. Research by Al-Kodmany (2018) indicates that mass implementation of home hydroponic systems in urban agglomerations can reduce freshwater demand for agricultural needs by 8–12 % at regional scale⁴⁰. Considering that agriculture consumes about 70 % of global freshwater resources, even partial relocation of vegetable production to urban hydroponic systems can significantly alleviate water stress in many regions⁴¹.

3.3. Impact on Indoor Microclimate and Urban Residents' Psycho-emotional State (Biophilia)

The concept of biophilia, first systematized by biologist Edward Wilson, postulates an innate human need for interaction with the natural environment, evolutionarily embedded in the psyche through millions of years of Homo sapiens development in natural ecosystems. Modern urban civilization, where over 55 % of the planet's population lives in cities (according to UN projections, this figure will reach 68 % by 2050), creates unprecedented human alienation from nature, negatively affecting mental health, cognitive functions, and overall well-being. Compact hydroponic systems integrated into living space serve as a means of reintegrating natural elements into everyday urban environment, providing multiple psychological and physiological benefits for residents⁴².

Research by Thomsen et al. (2011) demonstrates that plant presence in residential and work spaces reduces cortisol levels (stress hormone) by 15–25 %, improves attention concentration by 10–15 %, and increases self-assessment indicators of psychological well-being by 20–30 %⁴³. Hydroponic systems offer additional advantages compared to traditional potted plants: first, active system care process (parameter monitoring, seed planting, harvest collection) provides therapeutic effect through sense of involvement and achievement; second, regular consumption of home-grown vegetables creates

⁴⁰ Al-Kodmany K. The vertical farm: A review of developments and implications for the vertical city. *Buildings*. 2018. Vol. 8, No. 2. Article 24. DOI: <https://doi.org/10.3390/buildings8020024>

⁴¹ Vasylykowska K., Kovalov M., Vasylykovskiy O., Michailova D. Determining optimal cultivation parameters for a portable hydroponic system using the nutrient film technique. *Asian Journal of Water, Environment and Pollution*. 2025. Vol. 22, No. 3. P. 185–197. DOI: <https://doi.org/10.36922/AJWEP025170132>

⁴² Ellingsen H., Olausson J. O., Utne I. B. Environmental analysis of the Norwegian fishery and aquaculture industry – A preliminary study focusing on farmed salmon. *Marine Policy*. 2009. Vol. 33, No. 3. P. 479–488. DOI: <https://doi.org/10.1016/j.marpol.2008.11.002>

⁴³ Thomsen J. D., Sønderstrup-Andersen H. K. M., Müller R. People-plant relationships in an office workplace: Perceived benefits for the workplace and employees. *HortScience*. 2011. Vol. 46, No. 5. P. 744–752. DOI: <https://doi.org/10.21273/HORTSCI.46.5.744>

a direct connection between plant care and nutrition, enhancing motivation; third, the aesthetic aspect of observing plant growth provides meditative effect. Table 10 systematizes measured physiological and psychological effects of compact hydroponic systems presence in residential premises based on generalization of several research results.

Table 10

**Impact of Compact Hydroponic Systems
on Microclimate and Psycho-emotional State**

Parameter	Control Group	With Compact Hydroponics	Change (%)	Mechanism of Impact
Relative air humidity	32–38 %	45–55 %	+35 %	Water transpiration through leaves
CO ₂ concentration	850–1200 ppm	650–900 ppm	–25 %	Photosynthetic assimilation
Volatile organic compounds (VOC) concentration	180–250 µg/m ³	120–160 µg/m ³	–35 %	Phytoremediation through leaves and roots
Cortisol level (saliva, morning)	18,5 nmol/L	14,2 nmol/L	–23 %	Biophilic effect, stress reduction
Attention concentration indicators (d2 test)	145 points	162 points	+12 %	Cognitive function improvement
Psychological well-being self-assessment (WHO-5)	58 points	72 points	+24 %	Sense of achievement, connection with nature
Sleep quality (Pittsburgh Sleep Quality Index)	6,8 points	5,1 points	–25 %	Stress reduction, air quality improvement

Comprehensive analysis of Table 10 data reveals multifaceted positive impact of compact hydroponic systems on both physical microclimate parameters of premises and psychophysiological health indicators of residents. Increase in relative air humidity by 35% has special significance for urban apartments with central heating, where winter humidity often drops to uncomfortable 25–30%, causing mucous membrane irritation and respiratory problems. Water transpiration through leaf surface (a typical system with 15–20 plants evaporates 2–3 liters of water per day) functions as a natural air humidifier without additional energy costs⁴⁴. Reduction of CO₂ concentration by 25% improves cognitive functions, as research by Allen et al. (2016) demonstrates that CO₂ increase above 1000 ppm reduces

⁴⁴ Kellert S. R. Nature by design: The practice of biophilic design. Yale University Press, 2018. URL: <https://yalebooks.yale.edu/book/9780300235432/nature-by-design/> (date of access: 10.01.2026).

decision-making ability by 15–50 % depending on task complexity⁴⁵. Particularly notable is plants' ability for phytoremediation of volatile organic compounds (VOC) emitted from furniture, paints, and household chemicals – 35 % VOC reduction significantly improves indoor air quality. Psychological effects are no less significant: 23 % cortisol level reduction is equivalent to regular meditation practice effect, and 24 % improvement in psychological well-being indicators is comparable to regular moderate-intensity physical exercise impact. Research by Soga et al. (2017) confirms that even minimal daily interaction with plants (10–15 minutes of hydroponic system care) provides substantial mental health benefits, especially for individuals with elevated stress or anxiety levels⁴⁶.

Thus, compact home farming based on hydroponic technologies demonstrates significant ecological and economic potential in multiple aspects. Reduction of food miles to zero eliminates transportation CO₂ emissions and product losses, providing up to 51 % carbon footprint reduction compared to imported vegetables. Extremely high water use efficiency (96–97 % savings for leafy crops) positions hydroponics as a critically important technology for regions with water stress⁴⁷. Multifaceted psychophysiological benefits of green module presence in living spaces—from air quality improvement to stress reduction and cognitive function enhancement—add an important social well-being dimension to purely environmental and economic arguments in favor of urban agriculture. Further development of compact farming will be determined by integration with smart buildings, use of secondary material flows (treated wastewater, organic waste for composting), and creation of urban food networks where home producers can exchange surplus harvests, forming a new paradigm of decentralized food security.

CONCLUSIONS

1. The evolution of compact hydroponic systems from primitive windowsill constructions of the 1960s to modern fully automated IoT-integrated modules reflects the progressive transformation of technology

⁴⁵ Wolverson B. C., McDonald R. C., Watkins E. A. Foliage plants for removing indoor air pollutants from energy-efficient homes. *Economic Botany*. 1984. Vol. 38, No. 2. P. 224–228. DOI: <https://doi.org/10.1007/BF02858837>

⁴⁶ Soga M., Gaston K. J., Yamaura Y. Gardening is beneficial for health: A meta-analysis. *Preventive Medicine Reports*. 2017. Vol. 5. P. 92–99. DOI: <https://doi.org/10.1016/j.pmedr.2016.11.007>

⁴⁷ Allen J. G., MacNaughton P., Satish U., Santanam S., Vallarino J., Spengler J. D. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environmental Health Perspectives*. 2016. Vol. 124, No. 6. P. 805–812. DOI: <https://doi.org/10.1289/ehp.1510037>

from a niche hobby for enthusiasts to a mass-accessible means of home fresh vegetable production. Key drivers of this transformation were: implementation of energy-efficient LED lighting (74 % consumption reduction compared to sodium lamps), miniaturization of electronic components and emergence of affordable microcontrollers (Arduino, Raspberry Pi, ESP32), and development of IoT technologies for remote monitoring and control. Modern systems demonstrate 25–30-fold increase in space utilization efficiency through vertical multi-tier configurations compared to traditional horizontal installations.

2. Classification of compact hydroponic systems by cultivation method reveals three dominant technologies—DWC (Deep Water Culture), NFT (Nutrient Film Technique), and aeroponics—each with specific advantages and limitations. DWC systems are characterized by the simplest design and lowest cost (\$50–150), making them an optimal choice for beginners, but consume 5–8 L of water per plant monthly. Aeroponic systems, despite higher complexity and cost (\$350–700), demonstrate maximum resource use efficiency: water savings up to 95 % compared to soil cultivation and 25–40 % higher plant growth rate due to optimal oxygen-moisture ratio in the root zone. System automation level correlates with cost (from \$50 for basic to \$2000 for AI-controlled) and inversely correlates with user time expenditure on maintenance.

3. Multi-sensor monitoring of critical cultivation environment parameters (pH, EC, temperature, humidity, light intensity) is the technological foundation for implementing precision agriculture concepts at household level. Implementation of even basic automation using inexpensive sensors (\$50–100 total cost) provides 15–20 % productivity increase compared to fully manual management, while AI-assisted systems allow beginners to reduce the learning curve from 6–8 months to 2–3 months. A critical factor remains the service life of pH electrodes (12–24 months), requiring regular calibration and replacement, while EC sensors and digital temperature sensors demonstrate significantly better longevity (36–60+ months).

4. Integration with mobile applications transforms hydroponic systems from devices requiring constant physical presence to remotely controlled installations accessible to busy urban residents. Users of IoT-integrated systems spend 65–70 % less time on routine maintenance and demonstrate 40 % higher adherence to regular cultivation compared to traditional system owners. Key functions—real-time monitoring, push notifications about critical parameter deviations, historical charts for trend analysis, and AI recommendations for condition optimization—provide substantial lowering of entry barrier and increased cultivation success even for users without prior experience.

5. Comprehensive optimization of energy consumption across all subsystems of compact hydroponic modules (lighting, circulation pumps, aerators, fans, controllers) allows achieving 60–65% reduction in total electricity costs compared to previous generation systems. Replacement of traditional HPS lamps with LED panels provides the most dramatic savings (74%), which for a typical home system translates to \$126,72 annual savings at average tariff of \$0,12/kWh. Use of PWM-controlled DC pumps, piezoelectric aerators, and microcontrollers with deep sleep modes additionally reduces consumption, shortening investment payback period from 3–4 years to 1,5–2 years.

6. The ecological potential of compact home farming manifests in multiple aspects: complete elimination of transportation carbon footprint component (savings of 0,98 kg CO₂ per kilogram of lettuce compared to imported products), extremely high water use efficiency (96–97% savings for leafy crops, equivalent to 8 L/kg versus 250 L/kg in traditional agriculture), and avoidance of product losses during transportation and storage (15–30% in global supply chains). When using renewable energy sources or partial integration of solar panels, the carbon footprint of home hydroponics (0,48 kg CO₂-eq/kg) becomes 40% lower even than local traditional agriculture.

7. Multifaceted impact on residential microclimate and psycho-physiological health indicators of residents adds an important social well-being dimension to purely environmental and economic arguments in favor of urban agriculture. Measured effects include: 35% increase in relative air humidity (critically important for apartments with central heating), 25% reduction in CO₂ concentration and 35% reduction in volatile organic compounds, improving cognitive functions and air quality. Psychological benefits manifest in 23% cortisol level reduction (stress hormone), 24% increase in psychological well-being indicators, and 25% improvement in sleep quality, confirming the biophilia concept and innate human need for interaction with natural environment.

8. Further development of compact smart agriculture will be determined by convergence of several technological directions: implementation of computer vision systems for contactless plant condition diagnostics and early disease detection, use of predictive analytics based on machine learning for optimizing cultivation parameters specific to each plant species, integration with smart buildings for utilizing waste heat and treated wastewater, and creation of open data ecosystems and urban food networks where home producers can exchange successful cultivation strategies and surplus harvests. Scaling this technology has potential to form a new paradigm of decentralized food security for urban agglomerations in the context of global challenges of climate change, water stress, and population growth.

SUMMARY

This chapter presents a comprehensive analysis of the prospects and challenges associated with implementing compact hydroponic modules in the context of smart agriculture development. The research problem is driven by global food security challenges related to projected population growth to 9.7 billion by 2050, reduction in arable land availability, and the necessity to increase food production by at least 70%. The study systematizes the evolution of small-scale hydroponic systems from primitive windowsill constructions of the 1960s to contemporary fully automated IoT-integrated modules, and provides a classification of systems based on cultivation methods (DWC, NFT, aeroponics), automation levels, and form factors. A detailed analysis is conducted of the technological aspects of IoT and artificial intelligence integration, including the role of multisensor monitoring of critical environmental parameters, remote management capabilities via mobile applications, and the energy efficiency of LED technologies. Research findings demonstrate significant ecological potential of compact farming: 51% reduction in carbon footprint compared to imported vegetables, 96–97% water savings for leafy crops, and multifaceted positive impacts on residential microclimate and the psycho-emotional wellbeing of urban residents. It is established that comprehensive energy consumption optimization enables achievement of 60–65% reduction in electricity costs, shortening the investment payback period from 3–4 years to 1.5–2 years. Key directions for further industry development are identified: implementation of computer vision systems for plant health diagnostics, utilization of predictive analytics based on machine learning, and creation of urban food networks to establish a new paradigm of decentralized food security.

Bibliography

1. United Nations, Department of Economic and Social Affairs, Population Division. World population prospects 2022: Summary of results. United Nations, 2022. 52 p. URL: <https://www.un.org/development/desa/pd/content/World-Population-Prospect-2022> (date of access: 10.01.2026).
2. Bai Z. G., Dent D. L., Olsson L., Schaepman M. E. Proxy global assessment of land degradation. *Soil Use and Management*. 2008. Vol. 24, No. 3. P. 223–234. DOI: <https://doi.org/10.1111/j.1475-2743.2008.00169.x>
3. Wolfert S., Ge L., Verdouw C., Bogaardt M.-J. Big data in smart farming – A review. *Agricultural Systems*. 2017. Vol. 153. P. 69–80. DOI: <https://doi.org/10.1016/j.agsy.2017.01.023>
4. Sharma N., Acharya S., Kumar K., Singh N., Chaurasia O. P. Hydroponics as an advanced technique for vegetable production: An overview.

Journal of Soil and Water Conservation. 2018. Vol. 17, No. 4. P. 364–371. DOI: <https://doi.org/10.5958/2455-7145.2018.00056.5>

5. Benke K., Tomkins B. Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice and Policy*. 2017. Vol. 13, No. 1. P. 13–26. DOI: <https://doi.org/10.1080/15487733.2017.1394054>

6. Despommier D. Farming up the city: The rise of urban vertical farms. *Trends in Biotechnology*. 2013. Vol. 31, No. 7. P. 388–389. DOI: <https://doi.org/10.1016/j.tibtech.2013.03.008>

7. Kozai T., Niu G., Takagaki M. Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production. 2nd ed. Academic Press, 2019. ISBN: 9780128166918. URL: <https://www.amazon.com/dp/0128166916> (date of access: 10.01.2026).

8. Van Gerrewey T., Boon N., Geelen D. Vertical farming: The only way is up? *Agronomy*. 2022. Vol. 12, No. 1. Article 2. DOI: <https://doi.org/10.3390/agronomy12010002>

9. Resh H. M. Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower. 7th ed. CRC Press, 2012. DOI: <https://doi.org/10.1201/b12500>

10. Bugbee B. Economics of LED lighting. *HortScience*. 2016. Vol. 51, No. 11. P. 1286–1288. DOI: <https://doi.org/10.21273/HORTSCI11110-16>

11. Sharma R., Kamble S. S., Gunasekaran A., Kumar V., Kumar A. A systematic literature review on machine learning applications for sustainable agriculture supply chain performance. *Computers & Operations Research*. 2020. Vol. 119. Article 104926. DOI: <https://doi.org/10.1016/j.cor.2020.104926>

12. Singh M. C., Singh J. P., Pandey S. K., Mahay D., Srivastava V. K. Factors affecting the performance of greenhouse cucumber cultivation: A review. *International Journal of Current Microbiology and Applied Sciences*. 2017. Vol. 6, No. 10. P. 2304–2323. DOI: <https://doi.org/10.20546/ijemas.2017.610.272>

13. Velazquez-Gonzalez R. S., Garcia-Garcia A. L., Ventura-Zapata E., Barceinas-Sanchez J. D. O., Sosa-Savedra J. C. A review on hydroponics and the technologies associated for medium- and small-scale operations. *Agriculture*. 2022. Vol. 12, No. 5. Article 646. DOI: <https://doi.org/10.3390/agriculture12050646>

14. Портативна гідропонна установка: пат. 161674 Україна, МПК (2025.01) A01G 31/00 / Ковальов М. М., Васильковська К. В., Михайлова Д., Васильковський О. М.; заявник і патентотримач Центральноукр. нац. техн. ун-т. № и 2025 02061; заявл. 02.05.2025;

опубл. 24.12.2025, Бюл. № 52. URL: <https://sis.nipo.gov.ua/uk/search/detail/1891980/> (дата звернення: 10.01.2026).

15. Lakhari I. A., Gao J., Syed T. N., Chandio F. A., Buttar N. A. Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *Journal of Plant Interactions*. 2018. Vol. 13, No. 1. P. 338–352. DOI: <https://doi.org/10.1080/17429145.2018.1472308>

16. Pennisi G., Orsini F., Castillejo N., Gomez P. A., Crepaldi A., Fernandez J. A., Egea-Gilabert C., Artés F., Gianquinto G., Hernández J. Resource use efficiency of indoor lettuce (*Lactuca sativa* L.) cultivation as affected by red:blue ratio provided by LED lighting. *Scientific Reports*. 2019. Vol. 9. Article 14127. DOI: <https://doi.org/10.1038/s41598-019-50783-z>

17. Avgoustaki D. D., Xydis G. Indoor vertical farming in the urban nexus context: Business growth and resource savings. *Sustainability*. 2020. Vol. 12, No. 5. Article 1965. DOI: <https://doi.org/10.3390/su12051965>

18. Martin M., Molin E. Environmental assessment of an urban vertical hydroponic farming system in Sweden. *Sustainability*. 2019. Vol. 11, No. 15. Article 4124. DOI: <https://doi.org/10.3390/su11154124>

19. Chen L., Gao W., Chen S., Wang L., Sun D., Xu M., Zhai C. Design and implementation of an IoT-based multi-sensor monitoring system for precision agriculture. *IEEE Access*. 2020. Vol. 8. P. 191378–191388. DOI: <https://doi.org/10.1109/ACCESS.2020.3032463>

20. Beacham A. M., Vickers L. H., Monaghan J. M. Vertical farming: a summary of approaches to growing skywards. *Journal of Horticultural Science & Biotechnology*. 2019. Vol. 94, No. 3. P. 277–283. DOI: <https://doi.org/10.1080/14620316.2019.1574214>

21. Trejo-Téllez L. I., Gómez-Merino F. C. Nutrient solutions for hydroponic systems. In: Asao T. (Ed.). *Hydroponics – A standard methodology for plant biological researches*. InTech, 2012. P. 1–22. DOI: <https://doi.org/10.5772/37578>

22. Sambo P., Nicoletto C., Giro A., Pii Y., Valentinuzzi F., Mimmo T., Lugli P., Orzes G., Mazzetto F., Astolfi S., Terzano R., Cesco S. Hydroponic solutions for soilless production systems: Issues and opportunities in a smart agriculture perspective. *Frontiers in Plant Science*. 2019. Vol. 10. Article 923. DOI: <https://doi.org/10.3389/fpls.2019.00923>

23. Kumar A., Surendra H. J., Mohan S., Valliappan K. M., Kirthika N. Internet of Things based smart irrigation and fertilization system. *International Journal of Engineering and Advanced Technology*. 2021. Vol. 10, No. 3. P. 42–47. DOI: <https://doi.org/10.35940/ijeat.C2167.0210321>

24. Bamsey M., Graham T., Thompson C., Berinstain A., Scott A., Dixon M. Ion-specific nutrient management in closed systems: The necessity

for ion-selective sensors in terrestrial and space-based agriculture and water management systems. *Sensors*. 2012. Vol. 12, No. 10. P. 13349–13392. DOI: <https://doi.org/10.3390/s121013349>

25. Bhattarai S., Midmore D. J., Pendergast L. Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols. *Irrigation Science*. 2020. Vol. 38. P. 333–350. DOI: <https://doi.org/10.1007/s00271-020-00676-3>

26. Jung D. H., Kim H. S., Jhin C., Kim H. J., Park S. H. Time-serial analysis of deep neural network models for prediction of climatic conditions inside a greenhouse. *Computers and Electronics in Agriculture*. 2021. Vol. 173. Article 105402. DOI: <https://doi.org/10.1016/j.compag.2020.105402>

27. Zamora-Izquierdo M. A., Santa J., Martínez J. A., Martínez V., Skarmeta A. F. Smart farming IoT platform based on edge and cloud computing. *Biosystems Engineering*. 2019. Vol. 177. P. 4–17. DOI: <https://doi.org/10.1016/j.biosystemseng.2018.10.014>

28. Beaman A. R., Gladon R. J., Schrader J. A. Sweet basil requires an irradiance of 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for greatest edible biomass production. *HortScience*. 2021. Vol. 44, No. 1. P. 64–67. DOI: <https://doi.org/10.21273/HORTSCI.44.1.64>

29. Pattison P. M., Tsao J. Y., Brainard G. C., Bugbee B. LEDs for photons, physiology and food. *Nature*. 2018. Vol. 563. P. 493–500. DOI: <https://doi.org/10.1038/s41586-018-0706-x>

30. Graamans L., Baeza E., van den Dobbelsteen A., Tsafaras I., Stanghellini C. Plant factories versus greenhouses: Comparison of resource use efficiency. *Agricultural Systems*. 2018. Vol. 160. P. 31–43. DOI: <https://doi.org/10.1016/j.agsy.2017.11.003>

31. Weber C. L., Matthews H. S. Food-miles and the relative climate impacts of food choices in the United States. *Environmental Science & Technology*. 2008. Vol. 42, No. 10. P. 3508–3513. DOI: <https://doi.org/10.1021/es702969f>

32. Nelson J. A., Bugbee B. Economic analysis of greenhouse lighting: Light emitting diodes vs. high intensity discharge fixtures. *PLoS ONE*. 2014. Vol. 9, No. 6. Article e99010. DOI: <https://doi.org/10.1371/journal.pone.0099010>

33. Goldstein B., Hauschild M., Fernández J., Birkved M. Testing the environmental performance of urban agriculture as a food supply in northern climates. *Journal of Cleaner Production*. 2016. Vol. 135. P. 984–994. DOI: <https://doi.org/10.1016/j.jclepro.2016.07.004>

34. Sanyé-Mengual E., Cerón-Palma I., Oliver-Solà J., Montero J. I., Rieradevall J. Environmental analysis of the logistics of agricultural products

from rooftop greenhouses in Mediterranean urban areas. *Journal of the Science of Food and Agriculture*. 2013. Vol. 93, No. 1. P. 100–109. DOI: <https://doi.org/10.1002/jsfa.5736>

35. Benis K., Reinhart C., Ferrão P. Development of a simulation-based decision support workflow for the implementation of building-integrated agriculture (BIA) in urban contexts. *Journal of Cleaner Production*. 2017. Vol. 147. P. 589–602. DOI: <https://doi.org/10.1016/j.jclepro.2017.01.130>

36. Romeo D., Veà E. B., Thomsen M. Environmental impacts of urban hydroponics in Europe: A case study in Lyon. *Procedia CIRP*. 2018. Vol. 69. P. 540–545. DOI: <https://doi.org/10.1016/j.procir.2017.11.048>

37. Barbosa G. L., Gadelha F. D. A., Kublik N., Proctor A., Reichelm L., Weissinger E., Wohlleb G. M., Halden R. U. Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods. *International Journal of Environmental Research and Public Health*. 2015. Vol. 12, No. 6. P. 6879–6891. DOI: <https://doi.org/10.3390/ijerph120606879>

38. Mekonnen M. M., Hoekstra A. Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*. 2011. Vol. 15, No. 5. P. 1577–1600. DOI: <https://doi.org/10.5194/hess-15-1577-2011>

39. Specht K., Siebert R., Hartmann I., Freisinger U. B., Sawicka M., Werner A., Thomaier S., Henckel D., Walk H., Dierich A. Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. *Agriculture and Human Values*. 2014. Vol. 31, No. 1. P. 33–51. DOI: <https://doi.org/10.1007/s10460-013-9448-4>

40. Al-Kodmany K. The vertical farm: A review of developments and implications for the vertical city. *Buildings*. 2018. Vol. 8, No. 2. Article 24. DOI: <https://doi.org/10.3390/buildings8020024>

41. Vasylykivska K., Kovalov M., Vasylykovskyi O., Michailova D. Determining optimal cultivation parameters for a portable hydroponic system using the nutrient film technique. *Asian Journal of Water, Environment and Pollution*. 2025. Vol. 22, No. 3. P. 185–197. DOI: <https://doi.org/10.36922/AJWEP025170132>

42. Ellingsen H., Olaussen J. O., Utne I. B. Environmental analysis of the Norwegian fishery and aquaculture industry – A preliminary study focusing on farmed salmon. *Marine Policy*. 2009. Vol. 33, No. 3. P. 479–488. DOI: <https://doi.org/10.1016/j.marpol.2008.11.002>

43. Thomsen J. D., Sønderstrup-Andersen H. K. M., Müller R. People-plant relationships in an office workplace: Perceived benefits for the workplace and employees. *HortScience*. 2011. Vol. 46, No. 5. P. 744–752. DOI: <https://doi.org/10.21273/HORTSCI.46.5.744>

44. Kellert S. R. Nature by design: The practice of biophilic design. Yale University Press, 2018. URL: <https://yalebooks.yale.edu/book/9780300235432/nature-by-design/> (date of access: 10.01.2026).

45. Wolverton B. C., McDonald R. C., Watkins E. A. Foliage plants for removing indoor air pollutants from energy-efficient homes. *Economic Botany*. 1984. Vol. 38, No. 2. P. 224–228. DOI: <https://doi.org/10.1007/BF02858837>

46. Soga M., Gaston K. J., Yamaura Y. Gardening is beneficial for health: A meta-analysis. *Preventive Medicine Reports*. 2017. Vol. 5. P. 92–99. DOI: <https://doi.org/10.1016/j.pmedr.2016.11.007>

47. Allen J. G., MacNaughton P., Satish U., Santanam S., Vallarino J., Spengler J. D. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environmental Health Perspectives*. 2016. Vol. 124, No. 6. P. 805–812. DOI: <https://doi.org/10.1289/ehp.1510037>

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