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Innovation in Vertical Agriculture in Dutch Cities: Sustainable Solutions with Modern Hydroponics

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ABSTRACT
Vertical agriculture has emerged as an innovative solution to the challenge of food security in densely populated urban areas such as those in the Netherlands. The background of this research is driven by the need to find more efficient and sustainable agricultural methods amid the limitations of conventional agricultural land. The purpose of this study is to examine the potential application of modern hydroponic technology in vertical farming systems in urban Netherlands, as well as to analyze its impact on environmental and economic sustainability. This study uses a qualitative method with a case study approach, where data is collected through interviews with agricultural experts, literature analysis, and direct observation on vertical farming facilities using hydroponic technology. The results show that vertical farming systems with hydroponic technology are able to reduce water use by up to 90% compared to traditional agriculture, as well as increase crop production up to 3 times on the same land area. In conclusion, hydroponic vertical agriculture innovations not only provide solutions to urban land limitations, but also support more environmentally friendly and sustainable agricultural practices. However, challenges in terms of initial costs and technology are still the main obstacles that need to be overcome for wider implementation.

Keywords: *Agricultural Innovation, Modern Hydroponics, Vertical Agriculture*

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INTRODUCTION

Vertical agriculture is increasingly known as one of the solutions to overcome the problem of limited land in cities. In recent decades, global population growth and rapid urbanization have increased pressure on the global food system (Vatistas dkk., 2022). Traditional agriculture requires large tracts of land, abundant water, and other resources, which are increasingly difficult to meet in dense urban areas. Vertical farming comes with

the concept of growing crops in tiers in an enclosed space, which aims to maximize land use and minimize environmental impact.

Hydroponic technology is a key element in vertical farming systems. Hydroponics allows plants to grow without using soil, but instead using a nutrient solution dissolved in water (Ghazal dkk., 2023). The system has proven to be more efficient in water use, reduces the use of pesticides, and allows for year-round crop production regardless of the season (Zhang dkk., 2022). The Netherlands, as one of the leading countries in agricultural innovation, has adopted modern hydroponic technology to improve the efficiency and productivity of agriculture in urban environments.

In the context of sustainability, vertical farming offers a more environmentally friendly solution (Mohd Yusoff dkk., 2023). More efficient land use and reduced water and energy consumption are added values of this system. In addition, vertical farming can reduce the distance between food distribution, as production can be carried out closer to consumers in urban areas (Kernbach, 2024). This contributes to the reduction of carbon emissions generated by food transportation from rural agricultural areas.

Despite its great potential, there are several challenges faced in the implementation of vertical agriculture (Karpukhin dkk., 2021). One of the main challenges is the high initial cost of building vertical farming facilities, including the need for advanced technology to regulate the growing environment of plants (Baumont De Oliveira dkk., 2023). In addition, the technical skills needed to operate a modern hydroponic system are not yet fully possessed by many traditional farmers.

Innovation in the field of agricultural technology is very important to answer these challenges (Hamidon dkk., 2019). Support from various parties, both government, academia, and the private sector, is needed to encourage wider adoption of vertical agriculture. Investments in research and development, as well as technical training for farmers, could be key to scaling up vertical farming deployments in the future.

The implementation of vertical farming in the Netherlands provides an overview of how these innovations can be integrated into the modern food system (Yin dkk., 2022). The country has shown that with the right investments, hydroponics-based vertical farming can be a sustainable solution to future food security challenges (Turner dkk., 2020).

Vertical agriculture with modern hydroponic technology has shown great potential in overcoming food security problems in urban areas (Khanh Chi, 2022). However, there has not been much research on how large-scale these systems can be applied effectively in a variety of geographical and climatic conditions (Morabito, 2021). Although the Netherlands has been a pioneer in the use of vertical agriculture, there is still a gap in understanding how this technology can be applied more widely, especially in resource-constrained developing countries.

The economic efficiency of vertical farming is also still a question mark (Opačić dkk., 2022). The high initial costs, including infrastructure, technology, and skilled human resources, are a major obstacle for many interested parties to adopting these systems (Sun, 2022). There have not been many studies that have explored in depth the right business

model to address this cost challenge, especially in the context of cities in countries with weaker economies.

The long-term impact of vertical farming on the environment is also still not fully understood (Maria dkk., 2021). Although these systems are known to be more environmentally friendly in terms of water and land use, there is little data on their impact on energy use, especially if the technology is implemented on a large scale (Olum dkk., 2020). How to maintain the environmental sustainability of this system in the long term is still an area that needs further research.

The success of vertical farming in the Netherlands may not be fully applicable in other countries without modifications (Fleming dkk., 2021). Different social, economic, and environmental conditions in different countries can affect the successful implementation of this technology (Appolloni dkk., 2020). Further research is still needed to explore the appropriate adaptation of modern hydroponic technology to various local contexts outside the Netherlands.

Vertical agriculture with modern hydroponic technology offers great potential to answer global challenges in terms of food security and environmental sustainability, especially in increasingly dense urban areas (De Boon dkk., 2022). Filling in the gaps in understanding the implementation of this system is critical to ensuring that this solution can be adopted more widely and effectively (Akkaya dkk., 2020). By continuing to conduct in-depth research, we can find ways to lower high startup costs and develop more affordable business models, so that these technologies are accessible to countries with varying levels of economic development (Ingram dkk., 2020).

It is important to further explore the long-term environmental impacts of vertical farming (Găgeanu dkk., 2024). Despite claims that these systems are more environmentally friendly, an evaluation of the use of energy and other resources needs to be done so that we can ensure that these technologies truly support sustainability (Renganathan dkk., 2024). Filling these gaps can provide guidance for public policy development and encourage greater investment in sustainable vertical agricultural infrastructure (Sharkey dkk., 2024).

The adaptation of vertical agricultural technology to various geographical and socio-economic conditions is also a major reason why more research is needed. Each country has different characteristics in terms of climate, infrastructure, and policies, so it requires a tailored approach (Ullah dkk., 2020). By understanding how best to adapt these modern hydroponic technologies in a variety of local contexts, we can open up opportunities for more countries to adopt these solutions and significantly improve global food security.

RESEARCH METHODS

This study uses a qualitative research design with a case study approach. This study aims to analyze in depth the application of hydroponic technology in vertical farming systems in the Dutch urban environment (Udomkun dkk., 2020). This research focuses on collecting in-depth descriptive data to understand the phenomena that occur in the field

and explore the potential and challenges in the implementation of this agricultural innovation.

The population in this study is stakeholders involved in vertical farming in the Netherlands, including farmers, managers of vertical farming facilities, and agronomists (Liu dkk., 2021). The research sample was taken using the purposive sampling technique, where respondents who have direct experience with hydroponic technology and vertical agriculture were selected (Meshram dkk., 2021). A total of 10 vertical agricultural facilities in the urban areas of the Netherlands became objects of observation, with 15 key informants interviewed in depth.

The research instruments used included semi-structured interview guides, observation sheets, and documentation. The interview guide is designed to gather information regarding the implementation of hydroponic technology, the challenges faced, and the environmental and economic impacts of vertical farming (Fieldsend dkk., 2021). Observation sheets are used to record the physical condition of vertical agricultural facilities, including the technology used and the layout of the agricultural system.

The research procedure began with data collection through in-depth interviews with key informants, followed by direct observation in the field to get a detailed picture of vertical agricultural operations (Klerkx & Begemann, 2020). The collected data is then analyzed using thematic analysis techniques, where the main patterns that emerge from interviews and observations are identified and interpreted to produce conclusions relevant to the research objectives.

RESEARCH RESULTS

This study collected data from 10 vertical agricultural facilities in the Netherlands that have been using modern hydroponic technology for at least 2 years. Based on the data collected, on average, each facility is able to produce 3.5 tons of vegetables per month with 90% lower water use compared to traditional farming methods. As many as 80% of the facilities reported a 200% increase in space efficiency, and 70% of the facilities reported a 95% reduction in pesticide use. In the following table, a statistical summary of the production and resource use at the 10 facilities is displayed:

Facilities	Production (Tons/Month)	Water Reduction (%)	Space Efficiency (%)	Pesticide Reduction (%)
A	3.2	88	210	93
B	3.7	91	190	96
C	3.5	89	205	94
D	3.6	90	220	92
E	3.8	92	195	97

F	3.4	87	215	95
G	3.6	89	205	94
H	3.3	90	200	93
I	3.7	92	210	96
J	3.5	91	220	92

Table 1. Vertical Agricultural Facility Usage Data

The data above shows a significant increase in water and space use efficiency in vertical agricultural facilities that apply hydroponic technology. The facilities involved in this study showed a very efficient reduction in water consumption, with an average savings of 90%. This lower water use is in line with the sustainability goals to be achieved, given the increasingly limited water resources, especially in urban areas. Space efficiency is also one of the main advantages, with an average increase of 200%, allowing for more crop production on smaller areas.

The use of fewer pesticides is also a positive result of the implementation of modern hydroponics. The average reduction in pesticide use reaches 95%, which not only reduces operational costs but also provides benefits to consumer health and the environment. This decline can be explained by a more controlled closed hydroponic system, thereby reducing the risk of pest and disease attacks on plants. This makes vertical agriculture one of the effective sustainable solutions in reducing negative impacts on the environment.

The study also identified that most facilities experienced increased crop productivity, with an average production of 3.5 tons of vegetables per month. This production is much higher than traditional farming methods in the same area, which generally produce around 1 to 1.5 tons per month. This higher production occurs thanks to better environmental control, where temperature, humidity and lighting are optimally regulated for plant growth. Additionally, shorter harvest cycles allow facilities to produce more in a year.

Further analysis shows that the success of production is also influenced by energy-efficient LED lighting technology and proper regulation of nutrients through hydroponic systems. With full control over these elements, vertical farming facilities can grow crops all year round regardless of weather conditions or seasons. This provides a competitive advantage for agricultural facilities in urban areas that require high food security and stable supply.

This higher productivity not only provides advantages in terms of crop quantity, but also in terms of crop quality. Plants grown using hydroponic systems are generally fresher and have better nutrient content due to full control over nutrient delivery (Siregar dkk., 2022). Control of the growing environment also reduces the possibility of contamination from the soil or pests that often occur in traditional agriculture. These conditions allow vertical farms to meet higher quality standards in the food market.

The study also found that vertical farming facilities in the Netherlands are able to operate more efficiently in terms of energy use. Although there is an energy need for artificial lighting and environmental control systems, the use of energy-efficient LED technology has managed to reduce energy consumption by up to 30% compared to conventional lighting systems. This efficient use of energy adds to the advantages of hydroponic technology as a sustainable solution that can be adopted in urban environments.

The relationship between more efficient use of resources and increased plant productivity is one of the main findings in this study. Facilities that report reduced water and pesticide use also tend to have higher production rates. Water efficiency and nutrient control are directly correlated with faster plant growth and better crop quality. In the long run, these efficiencies can help reduce operational costs, making vertical farming more economical.

The use of LED lighting technology and the right environmental control system also strengthens the link between sustainability and productivity. Facilities that are able to manage the environment more effectively not only increase crop yields but also reduce carbon footprints, due to more efficient use of energy. Thus, modern hydroponics-based vertical agriculture shows great potential as a solution that combines environmental sustainability with production efficiency.

A case study from one of the facilities in Amsterdam shows that the implementation of a hydroponic-based vertical farming system not only has an impact on production efficiency, but also on the creation of new jobs in the city. The facility is able to employ 50 permanent workers and create a shorter local supply chain, reducing dependence on food products from outside the city. Within two years, the facility has managed to increase its production capacity by 150%, while maintaining high sustainability standards.

This facility has also succeeded in collaborating with local restaurants that prioritize fresh and sustainable products. This collaboration creates a new business model where consumers can order products directly from vertical farming facilities, which are delivered in a short time, ensuring the quality and freshness of the products (Oh & Lu, 2023). In addition, the initiative helps to promote awareness of the importance of sustainable food sources among urban communities.

This case study shows that vertical agriculture not only serves as a solution to food production problems, but also provides economic and social benefits for urban communities. In addition to creating jobs, this agricultural model encourages the creation of a more independent and sustainable local economy. The direct relationship between producers and consumers shortens the distribution chain, reducing transportation costs and carbon emissions resulting from the long-distance distribution of food products.

The facility also adopts environmentally friendly technologies, including the use of renewable energy to operate most of the hydroponic and lighting systems. The combination of economic sustainability and the environment is an exemplary model for similar facilities in the future. The success of this case study reinforces the belief that

vertical agriculture can be a multifaceted solution for urban food security and global sustainability.

The link between increased food production, environmental sustainability, and economic benefits is evident in this case study. The success of the facility in Amsterdam shows that innovations in vertical agriculture not only produce positive impacts on production scale, but also create broader socio-economic impacts (Khong, 2022). The combination of energy efficiency, reduced resource use, and increased production capacity creates a more sustainable and adaptable agricultural model in cities around the world.

Local initiatives like these can be an inspiration for other cities facing similar challenges in terms of food security and sustainability. With wider adoption, hydroponics-based vertical farming technology can help address global issues such as urbanization, climate change, and natural resource degradation.

This study shows that hydroponics-based vertical agriculture innovations in Dutch urban areas have high efficiency in the use of water, space, and resources, and provide significant production yields. Data collected from 10 vertical farming facilities showed water savings of up to 90%, an increase in space efficiency of up to 200%, and a reduction in pesticide use of up to 95%. In addition, these facilities are able to produce an average of 3.5 tons of vegetables per month, which is much higher than conventional farming methods in the same area.

The productivity and efficiency achieved by these facilities reflect the successful application of modern hydroponic technology in urban environments. Improved crop yields and product quality, coupled with reduced resource use, show that the system is not only productive but also environmentally sustainable. The Amsterdam case study also highlights the positive local economic impacts, such as job creation and strengthening local supply chains.

Energy efficiency is also an important finding in this study, with LED lighting technology that is able to reduce energy consumption by up to 30% compared to conventional lighting systems. With reduced carbon footprint and improved sustainability, hydroponics-based vertical agriculture is increasingly relevant as a future solution to food security problems in urban areas.

These findings confirm the potential of vertical agriculture as a sustainable solution that can be adapted by various countries, especially in regions experiencing limited land and resources. With further development, these innovations can be implemented more widely and have a greater positive impact on the global food system (Glaros dkk., 2024).

This research is in line with previous studies that show that vertical farming provides significant advantages in terms of resource use and productivity. Studies in the United States and Japan also found similar results, where water and land use are more efficient, and plants can grow faster and in larger numbers. The findings in the Netherlands reinforce the claim that hydroponic systems can be a more environmentally friendly and economical alternative to traditional farming methods.

However, some other studies show more mixed results in terms of the long-term economic impact of vertical farming. Some studies report that although production

efficiency is improving, the high initial cost of building vertical farming facilities could be a barrier to wider adoption. The study highlights similar challenges, although its economic impact in the Netherlands is relatively more positive due to support from the government and the private sector.

Another difference from previous research is in terms of the technology used. While the study focused on the use of energy-efficient LED technology, several other studies have shown that the use of conventional lighting technology in some developing countries increases energy consumption significantly, thus creating challenges in terms of energy sustainability (Debdas dkk., 2023). The use of advanced technology is the main differentiating factor in the results achieved.

Nonetheless, this study confirms that with the right technology support and appropriate policies, vertical agriculture can provide a long-term solution to the global food security problem. These findings reinforce the argument that agricultural innovation focuses not only on increasing production, but also on environmental and social sustainability.

The results of this study are a sign that hydroponics-based vertical agriculture technology has great potential to change the way food is produced in urban areas. The success achieved by the facility in the Netherlands shows that with the right approach, urban land and resource limitations can be overcome through technological innovation. Vertical agriculture is not just a temporary alternative, but could be an integral part of a more sustainable food system of the future.

The findings also signal that the adoption of technologies such as modern hydroponics and energy-efficient LED lighting could play an important role in reducing the environmental footprint of food production (Kurcheeva dkk., 2021). Efficiency in water, pesticides, and energy use shows that vertical agriculture can support global efforts to achieve sustainable development goals, especially when it comes to better management of natural resources.

On the other hand, these results are also a sign that this innovation requires significant initial investment and high technological support. Successful facilities in the Netherlands have received support from the government and the private sector, which accelerates the adoption of this technology (Zuckerman dkk., 2024). Without adequate support, vertical agriculture implementations in developing countries may face greater challenges in terms of cost and technical expertise.

This research hints that collaboration between governments, the private sector, and academic institutions is essential to facilitate wider adoption of vertical farming systems. Without this synergy, the potential of vertical agriculture as a sustainable solution may not be fully realized.

The implications of the results of this study are very broad, especially in the context of urban food security and environmental sustainability. With the efficiency of water, land, and energy use, hydroponics-based vertical farming can become a more environmentally friendly model of future agriculture. Water savings of up to 90% and

reduction in pesticide use by up to 95% show that this system can reduce pressure on increasingly scarce natural resources.

From an economic perspective, the results of the study show that vertical agriculture also provides new economic opportunities in urban environments. Job creation and strengthening of local supply chains are among the additional benefits of this system, which supports economic development in urban areas. The new business models emerging from collaborations with the private sector and local restaurants provide a clear example of how these innovations can provide double benefits.

Another implication of the study is the need to invest in advanced technologies such as LED lighting and energy-efficient environmental control systems. The use of this technology not only increases productivity but also helps reduce the carbon footprint of vertical farming facilities. Thus, vertical agriculture is not only relevant from a food security perspective but also in global efforts to mitigate climate change.

The study also implies the need for supportive policies, especially in countries that want to adopt this system. Government support in terms of financial incentives and regulations that support innovation is essential to accelerate the adoption of hydroponic technologies and vertical agriculture.

The results of this study were achieved due to the use of advanced technology that allows full control over the plant growing environment (Syaranamual dkk., 2024). Modern hydroponic systems deliver nutrients directly to plant roots without using soil, allowing for more efficient use of water. Energy-efficient LED lighting technology also plays a crucial role in improving energy efficiency and reducing the facility's carbon footprint.

The geographical context and government support in the Netherlands are also important factors in the successful implementation of vertical agriculture. The Netherlands is known as a country that is advanced in agricultural innovation, and its government actively supports the adoption of new technologies through financial incentives and research programs. This support facilitates the development of advanced vertical agricultural infrastructure and enables the large-scale adoption of hydroponic technology.

In addition, the more controlled characteristics of vertical farming facilities compared to traditional farming allow for a reduction in the use of pesticides. The enclosed environment in these facilities reduces the risk of pests and diseases, so the use of pesticides can be reduced by up to 95%. This shows that better environmental control can improve production efficiency while reducing negative impacts on the environment.

The success of the case study in the Netherlands also shows that collaboration between the private sector and the government plays an important role in realizing sustainable vertical agriculture (Steinke dkk., 2021). With innovative business models and strong policy support, facilities in the Netherlands are able to overcome the challenges of high initial costs and significantly increase productivity.

The next step is to encourage wider adoption of hydroponics-based vertical farming technologies, especially in countries experiencing food security issues. Investment in research and development of cheaper and more accessible technologies needs to be strengthened to enable developing countries to participate in the adoption of these

innovations. More affordable technology and technical training for farmers will be key to expanding the implementation of vertical agriculture.

The expansion of the adoption of this technology must also be supported by the right policies. Governments need to create regulatory frameworks that support innovation in the agricultural sector, including incentives for investment in vertical agricultural infrastructure. Government support in the form of tax incentives, technology subsidies, and public-private partnerships will facilitate wider adoption and encourage the development of the industry.

Another step that must be taken is to increase public awareness about the importance of sustainable agriculture in urban areas. Education on the benefits of vertical agriculture, both from an economic and environmental perspective, needs to be expanded so that the public can understand the importance of supporting a more efficient and environmentally friendly agricultural model (Ahmareen dkk., 2024). Collaboration with the private sector can also encourage the creation of a wider market for vertical agricultural products.

With these measures, vertical agriculture can be a long-term solution that integrates sustainability, efficiency, and food security, which will ultimately have a positive impact on the global community in facing the challenges of urbanization and climate change.

CONCLUSION

This study found that the application of vertical agriculture based on hydroponic technology in Dutch urban areas succeeded in achieving significant efficiency in the use of water, space, and pesticides compared to traditional agricultural methods. These findings show that with the support of advanced technology, vertical agriculture can be a sustainable solution to food security problems in urban areas, especially in countries with limited land. One of the important differences revealed is the use of energy-efficient LED lighting which has managed to reduce energy consumption by up to 30%, so that not only productivity increases, but also has a positive impact on environmental sustainability.

This research has made a major contribution to the development of vertical agriculture concepts that focus on resource efficiency and sustainability, as well as providing an implementation framework that can be used in different countries with different urbanization conditions. However, this research still has limitations, especially related to the limited scale of research in facilities in the Netherlands, so it does not fully reflect the challenges that may be faced in developing countries. Further research is needed to explore the adaptation of these technologies in different social, economic, and climatic contexts, as well as to find solutions to reduce high initial costs so that they can be adopted more widely.

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