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Integrated Aquaponic Vertical Farming as An Approach to Organic Agriculture: A Review

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Abstract

Integrated aquaponic vertical farming (IAVF), which combines aquaponics and vertical farming, is considered a modern and environmentally friendly method of farming. It takes sustainability a step further by making greater use of available resources, space, and the environment. This approach enables the co-farming of fish alongside plant growth using hydroponic methods, utilizing water instead of soil, in a vertically stacked system. This integration of aquaculture and hydroponics enables plants and fish to be cultivated together, with the waste produced from one system serving as nutrients for the other, thus closing the biological cycles of agriculture. IAVF is based on concepts of a circular economy and gradual farming expansion that seek to address contemporary food production challenges, such as the lack of freshwater, soil degradation, and greenhouse gas emissions. This overview presents the concept of IAVF, its historical development, and discusses the use of organic-based fertilizers for agricultural sustainability. It also states the aim and outline of the review article.

Keywords: Aquaponic, IAVF, Organic fertilizer, Vertical farming.

الزراعة العمودية المائية المتكاملة كطريقة للزراعة العضوية: مراجعة مقال

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الخلاصة

تُعتبر الزراعة العمودية المائية المتكاملة (IAVF)، التي تدمج الزراعة المائية مع الزراعة العمودية، نهجًا زراعيًا مبتكرًا وصديقًا للبيئة. فهي تُعزز الاستدامة من خلال تحسين استخدام الموارد والمساحة والبيئة. تتيح هذه الطريقة تربية الأسماك جنبًا إلى جنب مع النباتات باستخدام تقنيات الزراعة المائية، حيث يحل الماء محل التربة في نظام عمودي متراص. يتيح التكامل بين تربية الأحياء المائية والزراعة المائية زراعة النباتات والأسماك في آن واحد، حيث تُوفر نفايات أحد النظامين العناصر الغذائية للآخر، مما يُكمل الدورات البيولوجية الزراعية. انطلاقًا من مبادئ الاقتصاد الدائري والتوسع الزراعي التدريجي، تهدف IAVF إلى معالجة مشكلات إنتاج الغذاء الحالية، مثل نقص المياه العذبة وتدهور التربة وانبعاثات غازات الاحتباس الحراري. تُقدم هذه النظرة العامة IAVF، وتتتبع تطورها، وتناقش الأسمدة العضوية للزراعة المستدامة، مع تحديد أهداف المراجعة وهيكلها.

كلمات مفتاحية: الزراعة المائية العمودية المتكاملة IAVF، الأسمدة العضوية، الزراعة العمودية.

Introduction

Rapid urbanization, natural disasters, climate change, and the widespread use of chemicals and pesticides have severely harmed soil fertility, significantly reducing and degrading soil productivity and fertility (14 and 15). The greater climate variability, increasing temperatures, droughts, and unstable climatic conditions have greatly impacted water resources, with the spread of irrigation, pollution, and declining groundwater levels posing serious threats to watershed water resources (32). If this trend continues, global food production will need to grow by 50% by 2050. This would require additional arable land which is currently unavailable. Future projections suggest that per capita arable land will fall below 0.20 hectares by 2050, a third of the area available in 1970 (7 and 17). Given these challenges, food production today is considerably challenging for conventional soil-based agricultural production systems, which are the ones mainly affected. Improved, more efficient, and environmentally friendly modern agricultural practices are needed to make soil-based agriculture more sustainable (34). Soilless farming methods could provide the solution to the agricultural issues affecting modern society. Among them, integrated aquaponic vertical farming (IAVF) techniques could be an alternative to organic soil-based farming systems and a supplement for existing problems.

The IAVF represents a groundbreaking application in sustainable agriculture, combining aquaculture and vertical farming via an intracellular system designed to tackle environmental and agricultural challenges. In combating the structure of progressively unsustainable modern agriculture, IAVF arguably aligns with the tenets of sustainability, circular economy, and eco-friendly farming principles by emphasising optimal resource allocation through the recycling of fish waste for plant growth. Aquaponics is, therefore, a combination of aquaculture and hydroponics whereby fish waste is primarily used as a source of nutrients for plants cultivated in a soil-less environment (15 and 27).

Fish release ammonia as waste into the water, and the beneficial bacteria in the system convert the ammonia into nitrates which act as fertilizers for plants allowing crop production to be sustained naturally. Unlike traditional farming that requires vast tracts of land, vertical farming utilizes upright space to grow crops in structured layers, allowing for high-density production of edible plant materials, particularly in densely populated urban environments where land is limited (10). To summarize, IAVF is an agriculture model that saves water, reduces waste, and increase crop yields.

In the IAVF system, vegetables and fish can be grown and raised together with minimal use of external inputs, with the fish waste being used as organic fertilizer for the growth of vegetables. What is interesting about IAVF is its potential to solve some of the pressing problems in today's agriculture. As more and more of the world's populations become urbanized, there is a need for locally grown, sustainable sources of food. IAVF (indoor and outdoor) allows food to be grown in cities and reduces land use, transport emissions, and to improve food security (11). This particularly novel solution which uses fish waste water as a natural fertilizer for crops cultivated in a vertical farm could help minimize the need for chemical fertilizers, which are responsible for soil and water pollution. Its vertical orientation also makes the system the only currently sustainable option for year-round crop production, free of seasonal dependency, allowing this solution to play an essential role in climate change resilience. Thus, with further developments in technology and research, IAVF has the potential for developing key solutions to the challenges of food production in this century.

Overview of Integrated Aquaponic Vertical Farming:

As a system, aquaponics can be traced back to ancient agricultural practices, including the Aztecs (Chinampas) and the rice-fish farming systems of Southeast Asia, in which plants are grown along with aquatic organisms in a symbiotic environment (31). Modern aquaponics involves carefully-controlled and more technology-powered systems that integrate recirculating aquaculture and hydroponics into a single closed-loop ecosystem. There are numerous types of fish and plants that can be grown together in the vertical aquaponic system (Table 1).

Table 1: Fish and plants that can be grown together in a vertical aquaponic system.

Fish Species	Plant Species	Integration	Ref.
Tilapia (*Oreochromis niloticus*)	Lettuce (*Lactuca sativa*)	The lettuce grows quickly and needs moderate nutrients.	20
Catfish (*Ictalurus punctatus*)	Basil (*Ocimum basilicum*)	Basil thrives in nutrient-rich water from catfish systems.	40
Trout (*Oncorhynchus mykiss*)	Spinach (*Spinacia oleracea*)	Both require cool temperatures, ideal for temperate setups.	27
Barramundi (*Lates calcarifer*)	Kale (*Brassica oleracea*)	Warm water conditions suit both species well.	1
Koi (*Cyprinus carpio*)	Strawberries (*Fragaria × ananassa*)	Koi produce sufficient nutrients for fruiting plants like strawberries.	2
Carp (*Cyprinus carpio carpio*)	Watercress (*Nasturtium officinale*)	Watercress thrives in nutrient-rich, shallow systems.	30
Barramundi (*Lates calcarifer*)	Tomato (*Solanum lycopersicum*)	High nutrient output from Barramundi waste supports tomato growth.	13
Murray cod (*Maccullochella peelii peelii*)	Pepper (*Capsicum annuum*)	Cod require stable environments, while peppers thrive in controlled conditions.	14

Fish excreta nourish the plants (5,6), where plants primarily utilize nitrogenous waste produced by fish, particularly nitrates, converting them into plant biomass and naturally filter the water which is recirculated back into the fish tank. Time is an essential factor in aquaponics design (and the iteration process), influencing the number of resources used and the supply chain of nutrients (8). It reduces waste and the use of fertilizers and pesticides compared to traditional farming, thereby creating a friendly alternative to food production (41).

In contrast, vertical farming involves growing crops in vertically inclined stacked layers, or integrated into other multi-story facilities, like urban buildings, greenhouses, or vertical containers. These structures enable local food production in urban areas, significantly reducing the demand for transportation and storage (11). Vertical farming optimizes the use of space, reduces water needs, and facilitates year-round production (6), which is particularly beneficial in urban areas where arable land is limited. Creating a symbiosis of vertical farming with aquaponics (IAVF) allow both approaches to increase sustainability metrics and maximize output unit area while reducing resource and environmental impact (24). Irrespective of its limitations, IAVF systems have been a potential etiological alternative to tackle intra-urban ecological challenges where there is space constraint and the requirement for locally obtained fresh or organic food is on the rise (18).

The IAVF concept simply integrates aquaponics and vertical farming, as seen in Fig 1.

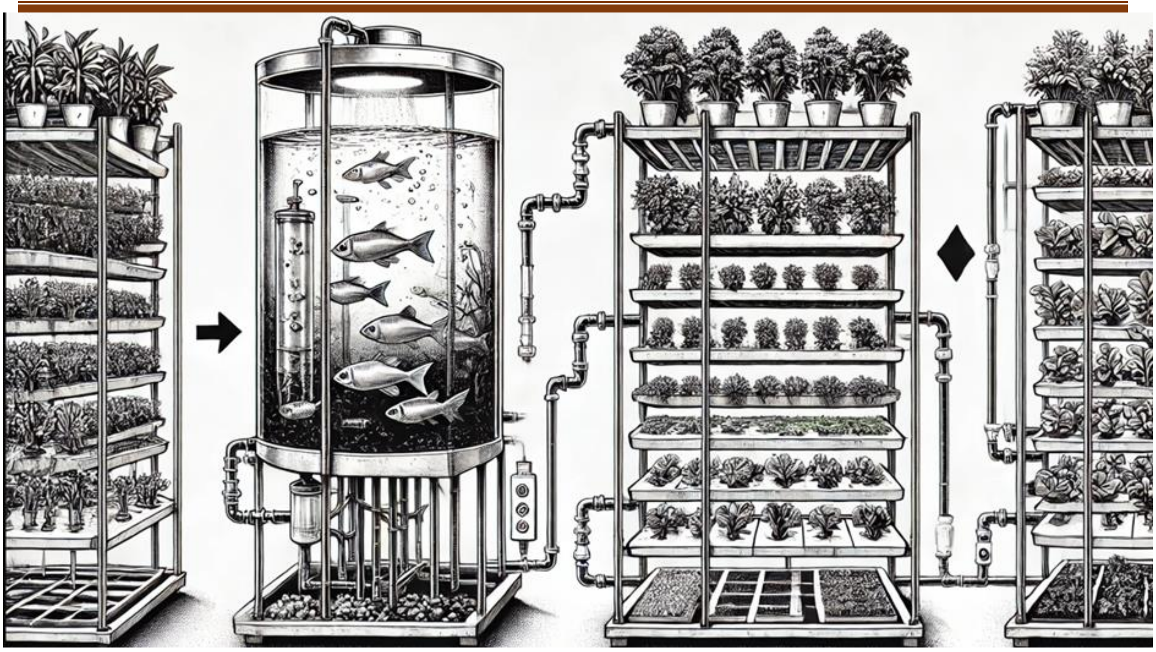

Fig. 1: Aquaponic system with a vertical farming tower.

Principles of Aquaponic Systems:

Aquaponics, a sustainable method of food production, integrates aquaculture (raising fish) and hydroponics (cultivating plants in water) to create a symbiotic environment where both plants and fish thrive. The system uses natural processes to cultivate both aquatic animals and plants in a recirculating ecosystem, minimizing waste and enhancing resource efficiency (15).

Basic Components of Aquaponics:

An aquaponic system comprises three main components, namely fish tanks, grow beds, and a water circulation system. The fish tanks are designed for freshwater species such as catfish, tilapia, and trout. Each fish species contributes distinct value to the system, influencing nutrition, water quality, and overall productivity (33). Grow beds provide the supporting structure for plant cultivation. They are typically filled with growth media like gravel, inert materials that support root systems, or expanded clay pellets that facilitate nutrient absorption. The water circulation system, the third essential component, transports water from the tanks to the grow beds, delivering nutrients to plants while maintaining clean water for the fish (40).

Aquaponic systems satisfy the needs of the fish and plants by actively controlling water circulation. Pumps circulate water through pipes from the tanks that house the fish to the grow beds, where fish waste nutrients are filtered for the plants to grow. Afterwards, the water is returned to the tanks (26). This system is particularly well-suited for dry or hot climates due to its low water demand (15).

Biological Processes in Aquaponics:

Several underlying biological factors influence the success of an aquaponic system, especially beneficial bacteria, and the nitrogen cycle. The nitrogen cycle begins with the fish excretion of ammonia, which is later turned into nitrites, which are vital for plants. Ammonia, a toxic byproduct, is converted into nitrites, and later nitrates, through a process called nitrification. The nitrification process is conducted by two forms of bacteria: Nitrosomonas and Nitrobacter. (40) stated that Nitrosomonas converts ammonia into nitrites, and Nitrobacter converts nitrites into nitrates. In aquaponic systems, water quality is maintained through efficient nitrification, otherwise it can cause increased levels of ammonia and nitrites, harming the fish.

Beneficial bacteria play a crucial role in the biological filtration stage of aquaponics. This biofilm can enhance organic matter decomposition and immersion in nitrogenous compounds. The healthy bacterial community has much influence on an aquaponic ecosystem as it affects nutrients that the plants rely on and increases the overall well-being of the aquatic plants (19).

Moreover, aquaponics systems must have a balance where fish stocking density, plant type and microbial activity must all interact with the best possible ratios or methods. The number of fish should be balanced to ensure that ammonia levels are controlled and do not stress or kill the fish (and possibly harm the plants). Similarly, insufficient plant population may cause excessive nutrient concentration and deteriorate water quality (33). Thus, a balanced ecosystem is required for the sustainability and productivity of aquaponics in the long run (26).

Vertical Farming Integration:

Vertical farming is a unique agricultural practice where crops are grown in vertically stacked layers. Plants are integrated within controlled environments such as buildings, shipping containers, or greenhouses. Vertical farming also allows for the cultivation of crops throughout the year in highly urbanized areas (10). In addition, aquaponic systems that work with other types of farming provide best practices that complement vertical farming in sustaining food production.

The combination of vertical farming and aquaponics improves food production while overcoming space limitations in urban areas. Vertical aquaponics is ideal for growing crops in confined spaces, and enhances food security and supply in urban areas (3) making urban centres more sustainable.

Fish Waste as Organic Fertilizer:

Animal waste and compost are the primary sources of organic fertilizers. They are eco-friendly and help the environment. Organic fertilizers are important in the agricultural sector because they allow crops to be cultivated sustainably while improving soil fertility, soil structure, and soil microbial activity (28) as well as minimize the adverse effects of conventional agriculture. The use of such organic fertilizers ultimately contributes greatly to soil and comprehensive health. This is important in farming as it improves the fertility and structure of the soil. Eventually, this leads to reduced environmental damage and helps establish sustainable practices for the future (28). In aquaponics systems, fish excretion waste is organic fertilizers (35). The waste is high in ammonia contents which is then converted into nitrates by the bacteria in the system. Nitrates serve as a natural nitrogen source for plants which is essential for plant development. Organic fertilizers take longer to release nutrients compared to chemical fertilizers, but this slow-release process helps keep nutrient levels consistent throughout the system.

The selection of organic or chemical fertilizers in aquaponic frameworks largely depends on the goals of the farmer. Compared to organic fertilizers, chemical fertilizers are more accessible and immediately supply the nutrients for plant absorption.

Nevertheless, they tend to disrupt the balance of aquaponic systems as well as contribute to pollution. On the other hand, organic fertilizers are a sustainable alternative that support soil activity, increases microbes, and reduces pollution, although they do require additional effort such as refining fuel (38 and 39). Despite these benefits, discrepancies in nutrient ratios and concentrations of organic fertilizers can be challenging. The nutrient equilibrium in aquaponic systems has to be stable, and ensuring that plants are provided with adequate nutrients is a delicate balance requiring good management (29).

The effectiveness of organic fertilizers in aquaponics is usually measured by their impact on plant growth and crop yield. Fish waste serves as a nutrient source, supplying essential macronutrients like nitrogen, phosphorus, and potassium, along with trace elements vital for plant development. Research has shown that plants grown in aquaponic systems, where fish manure is the primary nutrient source, yield results comparable to or even surpassing those achieved in traditional hydroponic systems that use chemical fertilizers (4). Moreover, (25) stated that microbial populations in the aquaponic root zone are necessary to increase nutrient absorption, enhance disease resistance, and support overall plant health.

Research demonstrates that organic fertilizers can positively support aquaponic systems. For example, (6) reported that aquaponically cultivated lettuce with fish waste exhibited increased quality and yield. In the same way, (37) confirmed that organic fertilizers were beneficial to the growth of spinach and kale. These observations highlight the opportunity of organic fertilizers to make aquaponic systems more sustainable and productive at the same time. There are, however, difficulties presented in using organic fertilizers in aquaponic systems. Different types of organic fertilizers can have varying nutrient composition and release rates, which can affect plant growth and yield. To sustain plant productivity and system balance, efficient management practices such as nutrient dosing and regular surveillance are critical (29).

Despite these challenges, the increasing demand for sustainable agriculture and organic food production is driving innovation in the use of organic fertilizers within aquaponics. Ongoing research and innovation efforts focus on improving nutrient management strategies and system efficiency, ultimately enhancing the sustainability and productivity of IAVF systems (15).

Benefits of IAVF:

Water efficiency is critical for the sustainability of IAVF which, unlike conventional agriculture, operates as a closed-loop system. Aquaponic systems can use up to 90% less water than conventional farming systems (16). Moreover, helping IAVF enhance the ability of the fish wastewater which is rich in nutrient solution to grow plants is a way to conserve water. IAVF also conserves water, promotes biodiversity and diversification in agricultural production. The integration of aquaculture and horticulture creates a symbiotic integration which allows for the simultaneous cultivation of protein-rich fish and nutrient-dense vegetables. This dual-output system strengthens the resilience of the food supply chain and helps mitigate the risk of food shortages (12). Besides, in conventional farming, synthetic fertilizers are heavily relied upon to fulfil the nutritional requirements of plants. However, they contribute to serious environmental issues, such as soil degradation, water pollution, and greenhouse gas emissions. IAVF decreases reliance on chemical fertilizers by utilizing fish waste as a natural fertilizer. The organic recycling of nutrients not only lessens the environmental impact of farming operations but also prevents nutrient runoff and aquatic eutrophication (6). Moreover, the natural and organic character of aquaponic systems is consistent with the concepts of organic agriculture and hence presents an economically sound option for substitution of chemical-based agricultural practices (15).

Challenges:

The IAVF system provides green solutions to urban agriculture through the integration of aquaculture and crop production in controlled environments. However, some challenges exist such as extensive use of electricity, huge initial capital, expensive equipment, and climate control systems that could be a significant setback to small-scale agricultural producers (36). Besides, nutrient control must be efficient since fish wastes are toxic, even though their property of providing nutrients for plant growth are well-known (9). Frequent checking of pH, electrical conductivity, and nutrient levels is critical to ensure system stability. Moreover, solid waste buildup can adversely affect water quality and interfere with nutrient cycling, therefore requiring efficient filtration and mineralization strategies (14). An appropriate choice of complementary fish species and plants is crucial since different species differ in their nutrient demands and tolerances and directly affect system design and operation (21).

Research and technological advancements are overcoming these challenges, with refinements such as automation, the inclusion of artificial intelligence, and the creation of low-cost, efficient system components rendering IAVF increasingly feasible. These advancements increase the scalability and economic viability of IAVF systems and aid sustainable urban farming initiatives, as well as address the global challenges of food security and climate change. With growing urbanization and deteriorating environmental conditions, even more significant demand will be made for resilient and resource-saving food production systems, putting IAVF at the forefront of future farming methods.

Conclusions

In conclusion, aquaponic systems integrated with vertical farming pave the way to a sustainable food production process. The incorporation of the two systems are beneficial in terms of nutrients circulation where the organic fish waste can be absorbed by the plants for their growth. This directly increases the economy of the farmer and the nation, while utilizing the urban spaces. The limited space in urban areas is no longer a challenge to produce agricultural foods. This approach also provides a sustainable and eco-friendly integration system to save resources and protect the environment.

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No Supplementary Materials.

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The authors declare no conflict of interest.

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References

1. Abdelfattah, S. W. H. A. (2023). Nutrient Optimization for Vegetable Production Under Decoupled Aquaponics Using Brackish Water (Master's thesis, The American University in Cairo (Egypt)).
2. Aguirre, J. P., Torres-Mesa, A., Perez-Trujillo, M. M., Rubio-Castro, S. A., and Gómez-Ramírez, E. (2023). Evaluation of Fragaria x ananassa in an aquaponic system with Oncorhynchus mykiss and substrate culture conditions. Aquaculture, Aquarium, Conservation and Legislation, 16(5): 2589-2600.
3. Akintuyi, O. B. (2024). Vertical farming in urban environments: a review of architectural integration and food security. Open Access Research Journal of Biology and Pharmacy, 10(2): 114-126. https://doi.org/10.53022/oarjbp.2024.10.2.0017.
4. Al Tawaha, A. R., Megat Wahab, P. E., and Jaafar, H. Z. (2025). Optimizing nutrient availability in decoupled recirculating aquaponic systems for enhanced plant productivity: a mini review. Nitrogen, 6(1): 3. https://doi.org/10.3390/nitrogen6010003.
5. Bhattacharjee, M. (2025). Sustainable Food Production Using Wastewater Aquaponics As An Environmentally Friendly System. International Journal of Agriculture and Environmental Research, 11(1): 270-288. https://doi.org/10.51193/IJAER.2025.11116

6. Besthorn, F. H. (2013). Vertical farming: Social work and sustainable urban agriculture in an age of global food crises. Australian social work, 66(2): 187-203. https://doi.org/10.1080/0312407X.2012.716448.
7. Bruinsma, J. (2017). World agriculture: towards 2015/2030: an FAO study. Routledge.
8. Colt, J., Schuur, A. M., Weaver, D., and Semmens, K. (2022). Engineering design of aquaponics systems. Reviews in Fisheries Science and Aquaculture, 30(1): 33-80. https://doi.org/10.1080/23308249.2021.1886240.
9. Delaide, B., Goddek, S., Gott, J., Soyeurt, H., and Jijakli, M. H. (2016). Lettuce (Lactuca sativa L. var. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. Water, 8(10): 467. https://doi.org/10.3390/w8100467.
10. Despommier, D. (2024). The vertical farm: feeding the world in the 21st century. Macmillan.
11. Despommier, D. (2020). Vertical farming systems for urban agriculture. In Achieving Sustainable Urban Agriculture (pp. 143-172). Burleigh Dodds Science Publishing.
12. Galanakis, C. M. (2024). The future of food. Foods, 13(4): 506. https://doi.org/10.3390/foods13040506.
13. Goddek, S., Delaide, B. P., Joyce, A., Wuertz, S., Jijakli, M. H., Gross, A., ... and Keesman, K. J. (2018). Nutrient mineralization and organic matter reduction performance of RAS-based sludge in sequential UASB-EGSB reactors. Aquacultural engineering, 83: 10-19. https://doi.org/10.1016/j.aquaeng.2018.07.003.
14. Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., and Thorarinsdottir, R. (2015). Challenges of sustainable and commercial aquaponics. Sustainability, 7(4): 4199-4224. https://doi.org/10.3390/su7044199.
15. Goddek, S., Joyce, A., Kotzen, B., and Burnell, G. M. (2019). Aquaponics food production systems: combined aquaculture and hydroponic production technologies for the future (p. 619). Springer Nature. DOI: 10.1007/978-3-030-15943-6.
16. Graber, A., and Junge, R. (2009). Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production. Desalination, 246(1-3): 147-156. https://doi.org/10.1016/j.desal.2008.03.048.
17. Grafton, R. Q., Daugbjerg, C., and Qureshi, M. E. (2015). Towards food security by 2050. Food Security, 7(2): 179-183. https://doi.org/10.1007/s12571-015-0445-x.
18. Junge, R., König, B., Villarroel, M., Komives, T., and Jijakli, M. H. (2017). Strategic points in aquaponics. Water, 9(3): 182. https://doi.org/10.3390/w9030182.
19. Kasozi, N., Abraham, B., Kaiser, H., and Wilhelmi, B. (2021). The complex microbiome in aquaponics: significance of the bacterial ecosystem. Annals of Microbiology, 71(1): 1. https://doi.org/10.1186/s13213-020-01613-5.
20. Khater, E. S., Bahnasawy, A., Mosa, H., Abbas, W., and Morsy, O. (2024). Nutrient supply systems and their effect on the performance of the Nile Tilapia

(Oreochromis niloticus) and Lettuce (Lactuca sativa) plant integration system. Scientific Reports, 14(1): 4229. https://doi.org/10.1038/s41598-024-54656-y.

21. Knaus, U., and Palm, H. W. (2017). Effects of the fish species choice on vegetables in aquaponics under spring-summer conditions in northern Germany (Mecklenburg Western Pomerania). Aquaculture, 473: 62-73. https://doi.org/10.1016/j.aquaculture.2017.01.020.
22. Lambin, E. F., Geist, H. J., and Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. Annual review of environment and resources, 28(1): 205-241. https://doi.org/10.1146/annurev.energy.28.050302.105459.
23. Lehmann, J., Bossio, D. A., Kögel-Knabner, I., and Rillig, M. C. (2020). The concept and future prospects of soil health. Nature Reviews Earth and Environment, 1(10): 544-553. https://doi.org/10.1038/s43017-020-0080-8.
24. Levizou, E., Mourantian, A., Chatzinikolaou, M., Feka, M., Karapanagiotidis, I., Mente, E., ... and Katsoulas, N. (2025). A circular tri-trophic system incorporating plants, fish, and insects turns waste into a resource: case study with the cultivation of cucumber. Frontiers in Plant Science, 16: 1638443.
25. Lobanov, V. P., Combot, D., Pelissier, P., Labbé, L., and Joyce, A. (2021). Improving plant health through nutrient remineralization in aquaponic systems. Frontiers in plant science, 12: 683690. https://doi.org/10.3389/fpls.2021.683690.
26. Love, D. C., Fry, J. P., Genello, L., Hill, E. S., Frederick, J. A., Li, X., and Semmens, K. (2014). An international survey of aquaponics practitioners. PloS one, 9(7): e102662. https://doi.org/10.1371/journal.pone.0102662.
27. Love, D. C., Fry, J. P., Li, X., Hill, E. S., Genello, L., Semmens, K., and Thompson, R. E. (2015). Commercial aquaponics production and profitability: Findings from an international survey. Aquaculture, 435: 67-74. https://doi.org/10.1016/j.aquaculture.2014.09.023.
28. Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P., and Borin, M. (2018). Hydroponic systems and water management in aquaponics: A review. Italian Journal of Agronomy, 13(1): 1012. https://doi.org/10.4081/ija.2017.1012.
29. Maucieri, C., Nicoletto, C., Zanin, G., Birolo, M., Trocino, A., Sambo, P., ... and Xiccato, G. (2019). Effect of stocking density of fish on water quality and growth performance of European Carp and leafy vegetables in a low-tech aquaponic system. PloS one, 14(5): e0217561. https://doi.org/10.1371/journal.pone.0217561.
30. Palm, H. W., Knaus, U., Appelbaum, S., Goddek, S., Strauch, S. M., Vermeulen, T., ... and Kotzen, B. (2018). Towards commercial aquaponics: a review of systems, designs, scales and nomenclature. Aquaculture international, 26(3): 813-842. https://doi.org/10.1007/s10499-018-0249-z.
31. Perumal, B., Shyam, S. N., Viswanath, S. S., Esa, M. M., Fatthah, P. A., and Rajesh, V. (2024, February). Smart Aquaponics Oversight: IoT Sensors and Mobile App Empowered Monitoring. In 2024 Second International Conference on Emerging Trends in Information Technology and Engineering (ICETITE) (pp. 1-4). IEEE.
32. Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., ... and Nandagopal, S. (2004). Water resources: agricultural and environmental

issues. BioScience, 54(10): 909-918. https://doi.org/10.1641/0006-3568(2004)054[0909:WRAAEI]2.0.CO;2.

33. Rakocy, J. E., Masser, M. P., and Losordo, T. M. (2006). Recirculating aquaculture tank production systems: Aquaponics-integrating fish and plant culture, Southern Region Aquaculture Center. SRAC Publication, 454.
34. Saraswat, S., and Jain, M. (2021). Adoption of vertical farming technique for sustainable agriculture. Climate Resilience and Environmental Sustainability Approaches: Global Lessons and Local Challenges, 185-201.
35. Shaji, H., Chandran, V., and Mathew, L. (2021). Organic fertilizers as a route to controlled release of nutrients. In Controlled Release Fertilizers for Sustainable Agriculture (pp. 231-245). Academic Press.
36. Somerville, C., Cohen, M., Pantanella, E., Stankus, A., and Lovatelli, A. (2014). Small-scale aquaponic food production: integrated fish and plant farming. FAO Fisheries and aquaculture technical paper, (589).
37. Tyson, R. V., Treadwell, D. D., and Simonne, E. H. (2011). Opportunities and challenges to sustainability in aquaponic systems. HortTechnology, 21(1): 6-13. https://doi.org/10.21273/HORTTECH.21.1.6.
38. Verma, B. C., Pramanik, P., and Bhaduri, D. (2019). Organic fertilizers for sustainable soil and environmental management. In Nutrient dynamics for sustainable crop production, 289-313. https://doi.org/10.1007/978-981-13-8660-2_10.
39. Verma, P., Singh, G., Singh, S. K., Bakshi, M., Mirza, A. A., Mehandi, S., and Vijayvargiya, V. (2025). Correlation, path-coefficient and principal component analysis association among quantitative traits in strawberry to unlock potential of vertical farming system. Kuwait Journal of Science, 52(1): 100303. https://doi.org/10.1016/j.kjs.2024.100303.
40. Wongkiew, S., Popp, B. N., and Khanal, S. K. (2018). Nitrogen recovery and nitrous oxide (N2O) emissions from aquaponic systems: influence of plant species and dissolved oxygen. International Biodeterioration and Biodegradation, 134: 117-126. https://doi.org/10.1016/j.ibiod.2018.08.008.