Journal of Advanced Agricultural Technologies, Vol. 11, No. 1, 2024

Multi-loop Aquaponics Systems: A Review and Proposed Multi-loop Agrogeological Aquaponics System

R. Mahkeswaran[1], Andrew Keong Ng[1,*], Chris Toh[2], and Brendan Toh[2]

[1] Engineering, Singapore Institute of Technology, Singapore
[2] Metro Farm Pte Ltd, Singapore
Email: R.Mahkeswaran@SingaporeTech.edu.sg (R.M.); Andrew.Ng@SingaporeTech.edu.sg (A.K.N.); Chris@MetroFarm.com.sg (C.T.); Brendan@MetroFarm.com.sg (B.T.)
*Corresponding author

***Abstract*—The achievement of the second sustainability development goal, targeting zero hunger by 2030, faces considerable challenges if the current food security landscape persists. Traditional agricultural practices remain inefficient and compete for space with the expanding global population. In contrast, urban agriculture presents a more resource-efficient and high-yield alternative by exploring soilless or alternative growing mediums in urban areas. Among the urban farming methods, aquaponics emerges as a noteworthy technique. A recent development in decoupled or multi-loop aquaponics systems aims to address the shortcomings of traditional systems. This paper, therefore, reviews various implementations of multi-loop aquaponics systems in literature, delving into their advantages and limitations. Incorporation of agrogeology into multi-loop aquaponics systems is potentially a strategy to tackle potential nutrient deficiencies that aquaponics systems may encounter. The design and construction of a proposed conceptual multi-loop aquaponics system with agrogeology are presented and discussed with suggestions for future research and development.**

***Keywords*—food security, aquaponics, decoupled aquaponics systems, multi-loop aquaponics systems, agrogeology**

I. INTRODUCTION

The second sustainable development goal of eradicating hunger by 2030 appears to be in doubt. The World Food Programme and World Health Organization have stated that the objective of achieving Zero Hunger by 2030 is unlikely to be met. Based on current patterns, the number of individuals impacted by hunger is projected to exceed 840 million by 2030 [1].

Conventional agriculture still contributes to 40% of the food production globally. Large amounts of water are required for this practice, which amounts to 90% of the global water consumption. However, only 55% of the water is absorbed and used by plants; the rest is lost as runoff. Runoff water carries excess pesticides and fertilizer into the surrounding environment, raising issues such as eutrophication. Aquaculture, the practice of rearing fish in submerged enclosures, also puts marine life in competition for space [2]. Being largely space-dependent, traditional agriculture is directly competing for space with the growing global population [3]. To feed a growing population, conventional farming largely relies on unsustainable practices to stay productive. Natural habitats are cleared in large areas to be converted to farmlands. This causes a large loss of wild fauna and flora, which can threaten ecosystems [2].

The shortcoming of conventional farming, coupled with the depletion of fertile land, reinforces the need to exploit other sustainable farming approaches. Studies have shown that effective farming can be done in urban areas [4]. Urban farming taps into soilless or techniques using alternative media to grow crops in residential or commercial areas. Urban farming techniques include hydroponics, aquaponics, aeroponics, and vertical farming [5]. Crops grown in hydroponics systems have their roots submerged in water dosed with nutrients, while aeroponics utilizes misting methods to spray nutrient-rich water directly onto roots [6]. The idea of vertical farming is to farm vertically as opposed to horizontally. Crops are grown vertically on building surfaces and rooftop stores in greenhouses or outdoors [7].

Aquaponics systems integrate aquaculture and hydroponics. Fish, plants, and naturally occurring nitrifying bacteria within the system live in a symbiotic relationship [8]. The working principle of aquaponics systems allows fish and vegetables to be produced simultaneously and organically. Consumers want to be assured that their food is healthy and chemical-free. The traditional type of aquaponics system is the single-loop aquaponics system. Single-loop aquaponics systems operate by water flowing in a single direction throughout the system. Hence, a middle ground of water parameters is maintained, producing crops with compromised health.

The latest development in aquaponics research is the introduction of decoupled aquaponics systems, also called Multi-loop Aquaponics Systems (MAS). These systems allow the hydroponics and aquaculture subsystems to

---

Manuscript received October 7, 2023; revised November 15, 2023; accepted November 30, 2023; published February 22, 2024.

doi: 10.18178/joaat.11.1.1-7

have their separate water flow, which enables better control of water parameters in each loop as ease of maintenance [9]. MAS are also highly scalable. The ability to easily add additional loops within MAS allows the introduction of various technologies as subsystems of the main aquaponics system. These technologies include distillation, anaerobic sludge blanket reactors, sludge digestors, and bio-floc units. These technologies mainly aim to further purify or process the water to benefit the fish grown in the system.

II. MULTI-LOOP AQUAPONICS SYSTEMS

The multitude of benefits MAS have over traditional aquaponics systems gave rise to many innovative variants. Modern MAS employ multiple loops for added control over the water parameters. MAS has an improved nutrient balance in the hydroponics subsystem. It enhances production quantity and the proportion of high-quality produce, such as lettuce with a higher dry weight fraction or tomatoes with reduced blossom-end rot. Since the environmental impact assessment considers the total resource use to the total quantity of products, implementing MAS brings down the overall environmental impact per production unit. Furthermore, integrating MAS into rooftop farming can yield energy savings [10].

A literature review aimed to explore the variants of MAS designs and their advantages over traditional single-loop systems. Papers obtained for this literature review are limited to conference papers published from 2017 to 2023 in popular scholarly databases like IEEE, SpringerLink, ScienceDirect, and Scopus. Comparisons will be made between the key design features of featured MAS and its viability of implementation at an industrial level.

III. VARIATIONS OF MULTI-LOOP AQUAPONICS SYSTEMS

A. *Multi-loop Aquaponics Systems with Desalination*

1) Working principle

To achieve optimal nutrient levels for plants and maintain low nutrient and particulate loading in fish tanks, it is necessary to continuously discharge suspended matter from the aquaculture component and add fertilizer to the plants. Desalination methods offer a potential solution by being able to extract dissolved salts and minerals from water.

Goddek *et al.* [11] demonstrated how integrating desalination processes can address specific technical issues in current decoupled aquaponics systems. A four-loop aquaponics system was proposed, consisting of a RAS loop, a hydroponics loop, a mineralization loop, and a desalination loop for nutrient concentration. The small-scale desalination unit aims to concentrate the hydroponics nutrient solution and direct demineralized water to the RAS subsystem. Implementing desalination processes can provide fresh water to the system and ensure the desired nutrient concentrations for the food-producing subsystems, reducing the need for additional fertilization [11].

On the other hand, Korner *et al.* [10] proposed designs for decoupled aquaponics simulation models, where a decoupled aquaponics system includes an optimally sized desalination unit and sludge bioreactor.

2) Advantages

The implementation of desalination technology in MAS systems can focus on three main aspects: (i) improving water quality in the RAS, (ii) increasing nutrient concentration from the RAS to the plants in the hydroponics loop, or (iii) a combination of both. Desalination technology has the potential to regulate RAS water quality to achieve desired levels and control nutrient concentrations in the hydroponics system. In addition to optimizing nutrient concentrations in each subsystem, desalination technologies can also be used to desalinate seawater or brackish water. This can enhance food production capabilities in dry regions. However, it should be noted that the energy and cost requirements of solar desalination technology are currently not competitive with fuel-based desalination methods [11].

3) Limitations

The current integration of desalination units into MAS relies on theoretical modelling approaches. Modelling desalination within MAS is a complex task that necessitates making several assumptions [11]. Integrating a desalination unit into a high-volume hydroponics sump would be challenging, as it is costly and requires significant energy input. Membrane desalination technology is not only expensive and energy-intensive but also susceptible to biofouling caused by bacteria and organic matter in the hydroponics nutrient solution. To address this issue, periodic backwashing and/or pre-treatment of the hydroponics solution are necessary. The presence of a large hydroponics sump offers a potential advantage by reducing the system’s vulnerability to nutrient fluctuations [11].

B. *Multi-loop Aquaponics Systems with Mineralization*

1) Working principle

Plant production relies on nutrients derived from fish waste. To enhance nutrient levels within the system, farmers raise the stocking density of fish. However, this practice can lead to an overaccumulation of nutrients, necessitating increased sludge removal through water discharge for operational purposes. This, in turn, results in the wastage of nutrients that could have been efficiently recycled by implementing a mineralization loop. Moreover, according to Tawaha *et al.* [12], it was observed that an increased stocking density does not result in a correspondingly higher plant yield.

The mineralization process involves the aerobic or anaerobic microbial digestion of the collected aquaculture waste, increasing the availability of nutrients for plant uptake. The mineralization technology holds substantial potential for recycling a significant proportion of macronutrients such as nitrogen, phosphorous, and potassium, especially when conducted under anaerobic conditions [13]. The system dynamics model presented by Goddek *et al.* [11] demonstrates that decoupled three-loop aquaponics systems rely on evapotranspiration and can benefit from including a mineralization loop. The system comprises a RAS loop, a hydroponics loop, and a mineralization loop. This multi-loop approach allows for the adaptation of environmental conditions in each loop to cater to species-specific requirements, minimizing trade-offs and enhancing growth performance. Rodgers *et al.* [14] also emphasized that in MAS systems, a significant advantage is the capture of solid fish effluent and wastewater that would typically be lost during filter backwash cycles. These waste products are then mineralized to create a nutrient solution that can be readily absorbed by plants.

2) Advantages

One of the advantages of MAS with mineralization is the recycling of nutrients, which contributes to environmental impact reductions while leading to a significantly higher lettuce yield [10]. Goddek *et al.* [11] proposed that integrating the anaerobic sludge mineralization loop into the RAS subsystem can promote denitrification. A separate mineralization loop, independent from the RAS and hydroponics loop, provides the benefit of supplying ammonium to the plants while ensuring optimal conditions for anaerobic bacteria [11].

The inclusion of the sludge remineralization process within a system holds significant potential. Beyond its role in nutrient supplementation, nutrient remineralization can be applied to accumulate nutrients in the hydroponics component. This offers a potential commercial advantage since the ratio between edible parts and residuals of plants, known as the root: shoot ratio, is influenced by the plant’s nutrient concentration [13]. Monsees *et al.* [15] also discovered that aerobic digestion enhances the mobilization of phosphorus and potassium, leading to increased availability of these nutrients.

3) Limitations

Determining the exact ratio of nutritional needs for different plant and fish species is complex due to various factors such as growth stage, life cycle, and external influences. Sludge thickening is necessary before the anaerobic digestion process, and an offline settling tank is commonly used for this purpose. In some cases, activated sludge denitrification reactors can be installed upstream of the UASB to place a portion of the carbon source to remove nitrate and reduce sludge volume. It is important to note that nitrogen recovery in anaerobic sludge treatment is highly dependent on hydraulic retention time and only marginal when the HRT exceeds several hours. Additional aerobic step in the MAS process produces additional biomass (i.e., bacterial growth) that consumes a portion of the available nutrients.

C. Multi-loop Aquaponics Systems with Bio-floc

1) Working principle

Aquaponics systems integrated with bio-floc (FLOCponics) are an offshoot of aquaponics where the traditional RAS is enhanced by a bio-floc technology (BFT) system. BFT manages water quality in aquaculture systems without requiring expensive mechanical and biological filters or extensive water exchange. In BFT, specific microbial communities are encouraged to develop in the aquaculture tanks through strong aeration and water movement. To ensure mature microbial communities in the moving bed biofilm reactor and bio-flocs, inoculums were often used. External carbon sources like liquid molasses are added to increase the carbon-to-nitrogen ratio and promote the growth of bio-floc microbiota, adding extra macro- and micronutrients to the water. Moreover, BFT exhibits lower nutrient loss than traditional RAS systems through minimal solids or sludge removal. The higher nutrient accumulation in FLOCponics water, resulting from BFT, can directly influence plant nutrition [16].

2) Advantages

This constant presence of nutrient-rich bio-floc microorganisms serves as a natural food source for the fish. As a result, better weight gain, survival rates, and feed conversion rates can be achieved compared to fish production in a traditional RAS. The consumption of bio-flocs by tilapia juveniles allows for the adaptation of nutritional strategies, such as using alternative protein ingredients instead of costly fish meals and soybean meals or reducing the protein content in diets. Studies have shown that even with a 30% reduction in dietary protein for tilapia reared in BFT, the fish exhibited more significant growth than those cultured in clear-water systems with 30% protein diets [16].

Tilapia juveniles fed with 32% crude protein and grown in bio-floc-based treatments showed a 22.7% higher growth than those in MAS without bio-floc. This indicates that consuming microbial bio-flocs as a complementary feed by tilapia is a significant factor contributing to improved growth. The use of FLOCponics production in a multi-loop layout allows for nutrient reuse from feed and a reduction in dietary protein, which can minimize the environmental impacts of aquaculture production. Multi-loop FLOCponics shows the potential to lower the crude protein content in fish diets compared to traditional MAS. The integration of plant production also does not compromise the nutritional benefits of BFT [16].

3) Limitations

Additional components must be built to post-process water from bio-floc before being supplied as plant irrigation. This can increase overall construction material usage and cost. Caroline *et al.* [17] implemented an aquaculture system operated as an autotrophic bio-floc system without applying an external nutrient source to stimulate bio-floc production. To remove suspended solids, including uneaten feed, feces, and microbial flocs, two passive clarifiers connected in series were needed to be employed. These clarifiers were cone-bottom tanks with a capacity of 1500 L each and were located outside the greenhouse adjacent to the aquaculture system. The aquaculture effluent needed to be continuously pumped into the first clarifier using an airlift, where it passed under a solid baffle that divided the tank into two halves. Subsequently, the effluent was transferred to the second clarifier, which served as the irrigation reservoir for the plant greenhouse. On average, the clarifiers removed 50% of the suspended solids from the aquaculture effluent before it was utilized for plant irrigation [17].

IV. PROPOSED MULTI-LOOP AGROGEOLOGICAL AQUAPONICS SYSTEM

A. *Introduction to Agrogeology*

From the literature review, it can be observed that importance is placed on addressing the nutrient balance in aquaponics systems. Aquaponics systems that rely solely on fish excreta are deficient in nitrogen, phosphorous, and potassium, resulting in suboptimal plant growth [18]. Therefore, there is a need to explore other avenues for naturally balancing nutrients in the aquaponics system.

Agrogeology is the practice of incorporating naturally occurring mineral rocks into agricultural soils, which act as slow-release fertilizers to supplement crop growth [19]. Some of these mineral rocks include diatomites, berg-meals, zeolites, phosphate rock, and various clays. Using agrogeology in conventional soil agriculture has substantially increased crop yield [20, 21]. These rocks are obtained as by-products of mining activities, known as Rock Mineral Powders (RMP), which are usually discarded. Recycling them for agriculture decreases the negative environmental impact of mining. When applied to soils, RMP can serve as a valuable source of multiple plant nutrients. Implementing such practices not only provides farmers with a cost-effective nutrient source but also offers a sustainable solution for the disposal of quarry by-products, creating additional value for these materials [20].

Diatomite is a sedimentary rock primarily composed of amorphous silica and formed through the accumulation of diatom algal fossils. Katerin *et al.* [21] conducted a study to investigate the response of sugarcane to diatomite fertilization in soil. The results revealed that the application of diatomite fertilizer positively influenced the growth of sugarcane plants with higher biomass and improved nutritional status. The application of diatomite also resulted in higher concentrations of nitrogen, phosphorus, manganese, copper, and zinc in the shoots of sugarcane plants [21]. Therefore, agrogeology can serve as a viable solution to organically enhance nutrient balance in MAS.

B. *Materials and Methods*

This paper proposes a system where a MAS incorporates agrogeology to potentially address nutrient imbalances in aquaponics systems coined as a Multi-loop Agrogeological Aquaponics System (MAAS). The MAAS consists of three main sub-components: the hydroponics section, the aquaculture section, and the filtration section. The hydroponics sections consist of a series of grow towers covering 81.458 m^2. The aquaculture section comprises three heptagon-shaped fish tanks spanning 3 m across with a 1 m height. The filtration section includes a media bed filter with a length, breadth, and height of (3.0×1.0×1.0) m^3 filled with selected agrogeology rocks and a sand filter. The water flow of the entire system is sustained by two water pumps with a capacity of 30,000 litres/hour each. Fig. 1 shows the MAAS at Metro Farm in Downtown East, Singapore.

1) *Hydroponics section*

The hydroponics section covers an area of 81.458 m^2, which is comprised of 125 evenly spaced-out vertical grow towers made of unplasticized polyvinyl chloride. The grow towers have a height of 1.9 m, each designed to accommodate up to 48 plants. Hydroponics sponges or rockwools are the supporting media for securing each plant within the towers upon planting. Water from the filter section is pumped to the top of each tower through connected pipes. Subsequently, the water trickles down each tower, delivering nutrient-rich water to the plant roots while providing effective aeration. The grow towers are interconnected to ensure that water collects at their base, and this combined water is subsequently pumped back into the fish tanks.

Fig. 1. Proposed multi-loop agrogeological aquaponics system.

2) *Aquaculture section*

The nutrient generation component of the MAAS is the aquaculture section, which features three heptagon-shaped fish tanks spanning 3 m in width and 1 m in height. The water depth in each tank is maintained at 0.7 m, resulting in a total volume of about 12,896.7 L of water. Chlorine-free fresh water is periodically added to compensate for water loss due to evaporation or leaks. Additionally, each tank is covered with a green plastic sunshade net, covering 70% of its surface area, to reduce evaporation and minimize sun exposure in the water column. Prolonged exposure of the water column to sunlight can lead to the development of algae blooms, which, in large quantities, can deplete nutrients from the aquaculture water and create other significant issues such as eutrophication [22].

3) *Filtration section*

The filtration section comprises two primary physical components: a biofilter tank and a sand filter, as depicted in Fig. 2. The biofilter tank, measuring 3.0 m by 1.0 m by 1.0 m, is filled with a high-surface-area media that facilitates the colonization of nitrifying bacteria. Maintaining a robust colony of nitrifying bacteria is crucial to ensure effective nitrification processes within the system, which convert ammonia in the water into nitrite and subsequently into nitrate. Nitrate is then absorbed by the plants in the hydroponics section to support their growth.

The biofilter tank also serves as the repository for agrogeology rocks. Specific types of agrogeology rocks can be used to supplement the corresponding deficient nutrients in the system. For instance, since phosphorus is a vital mineral nutrient for healthy plant development, phosphate rocks can be introduced into the system as a natural means of increasing phosphorous availability for the plants. Incorporating these natural mineral rocks into the biofilter tank also increases the overall surface area for nitrifying bacteria colonization. The sand filter eliminates any physical solids that may have been carried out of the biofilter tank, preventing large particles from causing damage to the pump blades.

4) Water flow

The MAAS can operate in either single-loop or multi-loop mode. This section will explain how water flows through the system in these operational modes. Fig. 3 depicts the simplified overview of how the different components of the MAAS are connected. Fig. 4 illustrates the system's water flow for each mode. Opened and closed valves are represented by green and red symbols, respectively. By manipulating the system's valves, the water flow within the system can be configured to follow either a single continuous path (single-loop mode) or to be divided into separate flows for the hydroponics loop and the aquaculture loop (multi-loop mode).

Fig. 2. Components in filtration section: (a) sand filter, (b) biofilter tank, (c) agrogeology rocks in mesh bag, and (d) agrogeology rocks.

There are several scenarios where the multi-loop configuration becomes essential. For instance, during maintenance procedures, when managing pest outbreaks, when introducing medications to the fish without affecting the plants or vice versa, or when adjusting water parameters to align with the specific requirements of the crop.

The farmer can switch between the single-loop and multi-loop configurations as needed. The single-loop mode proves advantageous when the farmer desires to raise only fish at a given time, eliminating concerns about compromising water parameters between fish and plants while offering an increased surface area for the growth of nitrifying bacteria on the unoccupied hydroponics towers. A system capable of transitioning between single-loop and multi-loop setups provides the farmer with enhanced control and flexibility in utilizing the system.

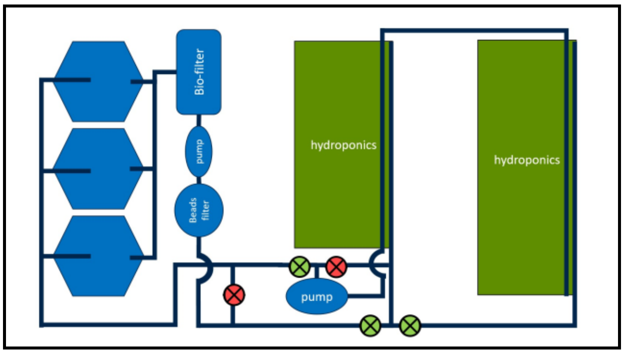

Fig. 3. Simplified diagram of multi-loop agrogeological aquaponics system.

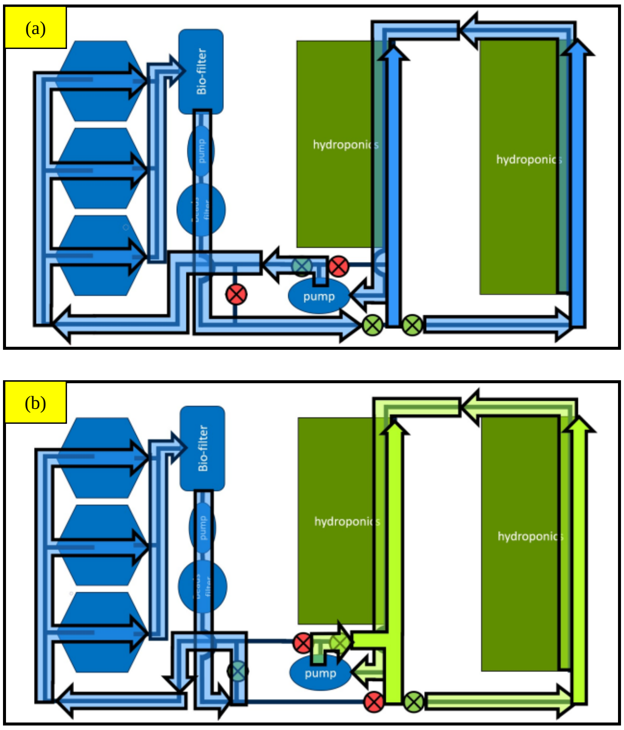

Fig. 4. System modes for multi-loop agrogeological aquaponics system: (a) single-loop mode and (b) multi-loop mode.

V. FUTURE WORKS

MAAS presents a potential alternative strategy for addressing nutrient deficiencies. Further exploration of this concept is needed to confirm the beneficial impact of incorporating agrogeology rocks. This could involve conducting growth studies to gain insights into the enhanced crop performance within the MAAS. Collecting data on fish growth, including length and weight measurements, over a growth cycle, and data on vegetable growth, such as leaf count, plant height, harvest weight, and dry weight, can help evaluate the influence of agrogeology.

The inclusion of technology into aquaponics systems has been shown to be beneficial. Internet of Things (IoT) devices, equipped with sensors, enable the transmission of vital farm data to farmers, enabling remote crop monitoring [23, 24]. Furthermore, they can activate instant messaging software to send early warning alerts and notifications to farmers, enabling prompt intervention to prevent deteriorating farm conditions [25]. Employing water nutrient sensors allows assessment of the nutrient content within the system's water, evaluating the MAAS's effectiveness in addressing the targeted nutrient deficiency.

To further increase the energy saving and efficiency of MAAS, the use of solar panels can be explored. Leveraging solar energy offers significant advantages due to its status as the most dependable and environmentally friendly source of renewable energy [26]. Selecting suitable solar panel arrangements for installation above crops can optimize the utilization of daylight while providing protection to crops from adverse weather conditions [27].

Advancements in technology, reductions in robot costs and sizes, and increased computing power have led to a notable rise in the adoption of intelligent robotics within the agricultural sector. Survey robots, for instance, can now traverse grow towers, enabling the identification of plant diseases or insect pests. These findings can then be remotely reported to farms [5]. On top of that, aquaponics systems can serve as a valuable educational tool, offering an interactive way for students to appreciate the importance of urban farming [28]. Consequently, this may pave the way for introducing more young individuals to embrace modern farming practices, ultimately enhancing food security.

VI. CONCLUSION

A comprehensive literature review focusing on MAS was carried out. The examination delved into various designs and proposals found in existing literature regarding MAS, discussing their advantages and limitations. The review highlighted that one of the key objectives of MAS is to address specific nutrient deficiencies crucial for optimal plant growth. The concept of agrogeology, which involves incorporating naturally occurring mineral rocks into agriculture to enhance crop development, was explored as a potential solution to nutrient deficiencies in MAS. Consequently, a proposed system – MAAS – was presented and discussed, in terms of its construction and operation. Lastly, as a prospect for future research and developments, recommendations were made for evaluating the effectiveness of the proposed system by analyzing crop health and growth data, with the aid of advanced technologies such as IoT, automation, artificial intelligence, and robotics.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

R. Mahkeswaran drafted this paper for publication, designed and developed the MAAS at Metro Farm in Downtown East, Singapore, with supervision from Andrew Keong Ng, the project principal investigator; Chris Toh and Brendan Toh, the industrial collaborators, supported the design and development of the MAAS; Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of the Ministry of Education, Singapore; All authors had approved the final version.

FUNDING

This research is supported by the Ministry of Education, Singapore, under SIT's Innovation Capability Grant project (R-MOE-A403-H016).

REFERENCES

[1] W. H. Organization, "The state of food security and nutrition in the world 2020: Transforming food systems for affordable healthy diets," *Food & Agriculture Org*, vol. 2020, 2020.

[2] A. Pradipta, *et al.*, "Remote sensing, geophysics, and modeling to support precision agriculture—Part 2: Irrigation management," *Water*, vol. 14, no. 7, 1157, Apr. 2022. doi: 10.3390/w14071157

[3] A. K. Verma, "Impacts of unsustainable farming on environment," pp. 59–62, 2017.

[4] K. S. Aishwarya, M. Harish, S. Prathibhashree, and K. Panimozhi, "Survey on automated aquponics based gardening approaches," in *Proc. Second International Conference on Inventive Communication and Computational Technologies*, 2018, pp. 1377–1381. doi: 10.1109/ICICCT.2018.8473155

[5] A. K. Ng and R. Mahkeswaran, "Emerging and disruptive technologies for urban farming: A review and assessment," *Journal of Physics: Conference series*, 2021. doi: 10.1088/1742-6596/2003/1/012008

[6] W. Vernandhes, N. S. Salahuddin, A. Kowanda, and S. P. Sari, "Smart aquaponic with monitoring and control system based on IoT," in *Proc. Second International Conference on Informatics and Computing*, 2017, pp. 1–6. doi: 10.1109/IAC.2017.8280590

[7] F. Rahman, I. J. Ritun, M. R. A. Biplob, N. Farhin, and J. Uddin, "Automated aeroponics system for indoor farming using Arduino," in *Proc. Joint 7th International Conference on Informatics, Electronics & Vision* and *2nd International Conference on Imaging, Vision & Pattern Recognition*, 2018, pp. 137–141. doi: 10.1109/ICIEV.2018.8641026

[8] K. Benke and B. Tomkins, "Future food-production systems: Vertical farming and controlled-environment agriculture," *Sustainability: Science, Practice and Policy*, vol. 13, no. 1, pp. 13–26, 2017.

[9] H. Monsees, W. Kloas, and S. Wuertz, "Comparison of coupled and decoupled aquaponics-Implications for future system design," *Abstract from Aquaculture Europe*, 2016.

[10] O. Körner, *et al.*, "Environmental impact assessment of local decoupled multi-loop aquaponics in an urban context," *J. Clean. Prod.*, vol. 313, 127735, 2021.

[11] S. Goddek and K. J. Keesman, "The necessity of desalination technology for designing and sizing multi-loop aquaponics systems," *Desalination*, vol. 428, pp. 76–85, 2018.

[12] A. R. A. Tawaha, P. E. M. Wahab, H. B. Jaafar, A. T. K. Zuan, and M. Z. Hassan, "Effects of fish stocking density on water quality, growth performance of tilapia and yield of butterhead lettuce grown in decoupled recirculation aquaponic systems," *Journal of Ecological Engineering*, vol. 22, no. 1, pp. 8–19, 2021.

[13] S. Goddek, *et al.*, “Navigating towards decoupled aquaponic systems: A system dynamics design approach,” *Water*, vol. 8, no. 7, p. 303, 2016.

[14] D. Rodgers, E. Won, M. B. Timmons, and N. Mattson, “Complementary nutrients in decoupled aquaponics enhance basil performance,” *Horticulturae*, vol. 8, no. 2, p. 111, 2022.

[15] H. Monsees, J. Keitel, M. Paul, W. Kloas, and S. Wuertz, “Potential of aquacultural sludge treatment for aquaponics: evaluation of nutrient mobilization under aerobic and anaerobic conditions,” *Aquac. Environ. Interact.*, vol. 9, pp. 9–18, 2017.

[16] S. M. Pinho, *et al.*, “Decoupled FLOCponics systems as an alternative approach to reduce the protein level of tilapia juveniles’ diet in integrated agri-aquaculture production,” *Aquaculture*, vol. 543, 736932, 2021.

[17] C. Blanchard, D. E. Wells, J. M. Pickens, and D. M. Blersch, “Effect of pH on cucumber growth and nutrient availability in a decoupled aquaponic system with minimal solids removal,” *Horticulturae*, vol. 6, no. 1, p. 10, 2020.

[18] M. F. Taha, *et al.*, “Using deep convolutional neural network for image-based diagnosis of nutrient deficiencies in plants grown in aquaponics,” *Chemosensors*, vol. 10, no. 2, p. 45, 2022.

[19] P. Swoboda, “Rock dust as agricultural soil amendment: A review,” *Doctoral dissertation, Karl-Franzens-Universität Graz*, 2016.

[20] B. B. Basak, B. Sarkar, and R. Naidu, “Environmentally safe release of plant available potassium and micronutrients from organically amended rock mineral powder,” *Environ Geochem Health*, vol. 43, pp. 3273–3286, 2021.

[21] K. M. E. Oliva, *et al.*, “Biomass and concentration of nutrients and silicon in sugarcane grown on soil fertilized with diatomite,” *Revista Brasileira de Ciências Agrárias*, vol. 15, no. 4, pp. 1–7, 2020.

[22] M. L. S. Diego-McGlone, R. V. Azanza, C. L. Villanoy, and G. S. Jacinto, “Eutrophic waters, algal bloom and fish kill in fish farming areas in Bolinao, Pangasinan, Philippines,” *Mar. Pollut. Bull.*, vol. 57, no. 6–12, pp. 295–301, 2008.

[23] R. Mahkeswaran and A. K. Ng, “Smart and sustainable home aquaponics system with feature-rich internet of things mobile application,” in *Proc. 6th International Conference on Control, Automation and Robotics*, 2020, pp. 607–611. doi: 10.1109/ICCAR49639.2020.9108041

[24] Z. J. Ong, A. K. Ng, and T. Y. Kyaw, “Intelligent outdoor aquaponics with automated grow lights and internet of things,” in *Proc. IEEE International Conference on Mechatronics and Automation*, 2019, pp. 1778–1783. doi: 10.1109/ICMA.2019.8816577

[25] T. Y. Kyaw and A. K. Ng, “Smart aquaponics system for urban farming,” *Energy Procedia*, vol. 143, pp. 342–347, 2017. doi: 10.1016/j.egypro.2017.12.694

[26] J. K. Tharamuttam and A. K. Ng, “Design and development of an automatic solar tracker,” *Energy Procedia*, vol. 143, pp. 629–634, 2017. doi: 10.1016/j.egypro.2017.12.738

[27] R. X. Teng, S. C. Chien, and A. K. Ng, “Harnessing sunlight for sustainable urban farming: Optimising photovoltaics in tropical container-based aquaponics systems,” in *Proc. 14th Asia Lighting Conference*, 2023, pp. 1–8.

[28] A. K. Ng and R. Mahkeswaran, “Fostering computational thinking and systems thinking through aquaponics capstone projects,” in *Proc. IEEE International Conference on Engineering, Technology & Education*, 2021, pp. 1039–1044. doi: 10.1109/TALE52509.2021.9678854