

Digital Twin And Interactive AR For Smart Aquaponics Iot Systems: A Preliminary Study

¹Rahmita Wirza O.K. Rahmat, ²Phang Kok Wai*, ³Siti Khadijah binti Ali and ⁴Zainal bin Abdul Kahar

^{1,2,3,4}Department of Multimedia, Faculty of Computer Science and Information Technology, University Putra Malaysia, Selangor, 43300 Malaysia

abstract

This study investigates how to adopt Digital Twin technology in Augmented Reality (AR) inside an IoT-based aquaponics system, not only to enhance real-time monitoring, visualization of data, and decision-making but also to establish control over the system. On the other hand, the aforementioned system includes an interactive AR interface visualizing data from IoT sensors in which users can experience real-time monitoring of important parameters in aquaponics, such as water level, water temperature, water pH, light intensity, surrounding temperature, and surrounding humidity. Feedback was collected via a structured survey from users through a structured survey to evaluate the usability and effectiveness of the system. Results indicate effective improvement of data visualization as well as decision-making, and enhancement for areas such as interface design and system interaction. Thus, it has been beneficial to the field by providing empirical insights into how Digital Twin and AR technologies can be applied to the management of aquaponics and recommendations for enhancing the system's usability and extending its adoption.

Keyword: Digital Twin, Augmented Reality, Internet of Things, Aquaponics, Smart Agriculture

1.0 INTRODUCTION

Aquaponics is an innovative, sustainable agricultural practice through which aquaculture (fish farming) and hydroponics (soil-free plant cultivation) are linked in such a way that the waste from fish is converted or made available for use in nutrients for plants while the plants filter or purify the water for the fish as shown figure 1.0. This closed-loop system saves water as much as 90% compared to conventional farming while also eliminating the need for synthetic fertilizers, leading to a far more sustainable food production framework (BambhaniyaI et al., 2003). However, it is quite difficult to keep an aquaponic system, as its parameters such as water level, water temperature, water pH, surrounding temperature, surrounding humidity, and light intensity have to be monitored continuously for the well-being of the plants and fish, which makes it challenging for the people operating the system, as he has to approach all what is monitored and checked manually, creating a lot of consumption of time, inefficient, and more prone to human error, especially in very large or complex systems (Reyes Yanes et al., 2022).

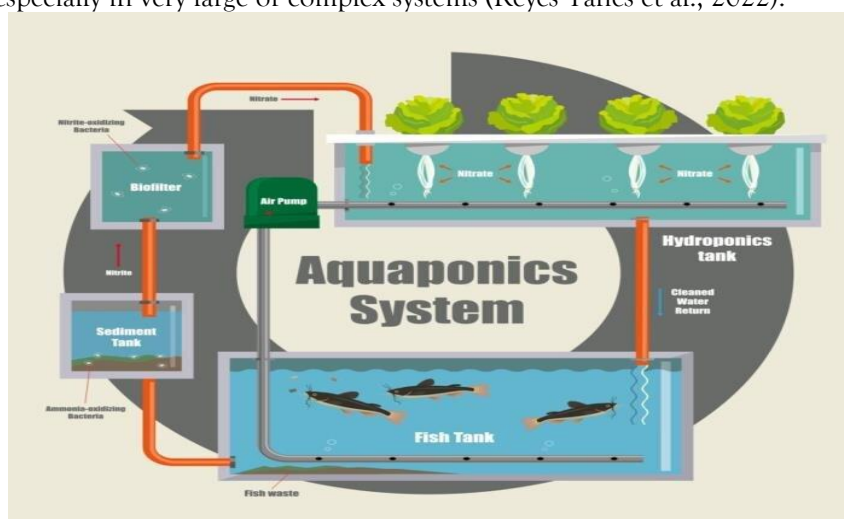


Figure 1.0 Illustration of an Aquaponics System (BambhaniyaI et al., 2003)

While aquaponics has its advantages, managing the systems remains quite a challenge. The interaction of various parameters like nutrient concentrations, water temperature, pH, and solubilized oxygen requires

live data to manage the system correctly. Since it is a complex system, automatic systems will need to be integrated with state-of-the-art technologies for optimal performance, such as Digital Twin and Internet of Things (IoTs) (Menon, 2020). The Digital Twin conceptualizes a digital resemblance of a physical system and has been widely embraced by industries for simulating, monitoring, and predicting the performance of that system. Using Digital Twin, aquaponics would replicate the entire system, tracking key parameters and predictive insights for optimizing the system's operation. (Verdouw et al., 2021)

Indeed, the Digital Twin is, since its technology would be based on real-time data collected from IoT sensors throughout the aquaponics facilities, continuously monitored and possibly maintained personally to ensure that everything remains within ideal intervals. Water quality, water temperature, and water levels are also monitored by these sensors, by collecting continuous data and forwarding it to the Digital Twin. In effect, this integration of IoT-enabled Digital Twin technology represents a significant advancement in aquaponic system management by delivering an unprecedented kind of real-time, precise monitoring and predictive capabilities.

While aquaponics had its advantages, managing these systems was quite a challenge. This includes the interaction that contributes to defining various parameters such as water temperature, water level, water pH, light intensity, surrounding humidity, and surrounding temperature, all of which need live data for the correct management of the system. Since adjustment of several parameters requires automation, this is where advanced technologies such as the Digital Twin and the Internet of Things come into play. The Digital Twin's concept - that of creating a digital replica of a physical system - has gained wide acceptance in industries as a means of simulating, monitoring, and predicting system performance. In aquaponics, a Digital Twin can replicate the entire system by tracking the key parameters of the system and offering predictive insights to optimize the system's operation.

Thus, the Digital Twin is based its technology on real-time data collected from IoT sensors spread all through the aquaponics.

The system provides an uninterrupted monitoring stream by taking care of all conditions while all these are kept in their optimal ranges. These sensors will continuously collect data, which is then sent off to the Digital Twin for analysis. In reality, this general integration of IoT-enabled Digital Twin technology marks a significant milestone in aquaponic systems management unimaginable before.

Augmented Reality (AR) tends to be yet another transformative technology that complements Digital Twin systems. AR adds to the physical world those layers of digital data that are meant to offer an interactive experience to users. In aquaponics, AR can extend the management of a system to provide an interactive, real-time visualization of critical metrics such as water level, water temperature, water pH, light intensity, surrounding temperature, and surrounding humidity. Operators may conduct real-time monitoring and adjustment with environmental parameters directly from the AR view since AR interfaces allow interaction within this structure. This method proves to be of assistance for the users in understanding data definitions in a very engaging manner without scouring raw numbers or many screens. Indeed, studies have indicated that AR technology enhanced user engagement and improved decision-making through an interface that was more interactive and easier to grasp to monitor system conditions. The synergetic involvement of Digital Twin, IoT, and AR technologies ensures much greater efficiency in management and optimization in aquaponics systems. Real-time monitoring, predictive modelling, and immersive visualization of the system performance thus improve ecological as well as operational efficiency. The rise of urban farming is a clearer consequence, particularly in areas where space or resources are constrained. The present approach tends to optimize available resources toward improving food security and minimizing environmental impact. The combination of Digital Twin and AR among IoT-enabled aquaponics innovations is an excellent new response to modern farming challenges that can usher in significant gains toward scalable, sustainable practice in urban farming.

The research encompasses the fusion of Digital Twin Interactive Augmented Reality (DTIAR) with IoT for aquaponics system applications. This study will investigate how DTIAR integration can enhance household system management, improve interactivity, and be resource-efficient to contribute to a sustainable and optimal practice in agricultural systems.

1.1 Problem Statements

Aquaponics is a sustainable agricultural method that can be quite complicated due to the potential

damage to key parameters, monitoring, and management. Although the Internet of Things brought some improvement in terms of automation, and the Digital Twin technology also made synergistic contributions to automation, there were still gaps between user interaction and scalability. This study aims to pinpoint the following specific issues:

- Manual monitoring of aquaponics parameters, including parameters such as water pH, temperature, and nutrient levels, is time-consuming, error-prone, and inefficient, particularly in large-scale systems.
- Most present IoT and Digital Twin systems do not provide intuitive user interfaces focused on the user, making it complex for individuals who are not tech-savvy to interpret and react to data from the system.
- There has been very little research on the application of augmented reality (AR) for aquaponics to be integrated with IoT and DT frameworks, which limits the interaction of users with real-time system data, consequently narrowing its adoption.

1.2 Research Objectives

In light of the identified problems, this study aims to achieve the following objectives:

- To design and develop a Digital Twin Interactive Augmented Reality (DTIAR) system to associate IoT sensors, DT simulations, and AR interfaces for real-time aquaponics systems monitoring.
- To evaluate usability, interactivity, and effectiveness of the DTIAR system through well-structured, systematic user testing and feedback.
- To make a number of pragmatic recommendations to improve accessibility, scalability, and the adoption of this DTIAR system for smallholder farmers and non-technical users.

1.3 Research Contribution

This research makes an important contribution to smart agriculture by integrating emerging technologies in aquaponics systems:

- **Technological Novelty:** The new integration of Digital Twin (DT), Internet of Things (IoT), and augmented reality (AR) offers an immersive and user-friendly interface for real-time monitoring of aquaponics systems.
- **Empirical Findings:** The present study records real evidence from user testing promoting usability and decision-making efficiency; 72% of users noted a preference for interactivity in the given system.
- **Practical Implications:** The present study provides a platform for affordable, scalable, and accessible AR interfaces that can contribute to the UN's Sustainable Development Goals (SDGs) on food security and sustainable agriculture, thereby providing support for the application of smart farming solutions in resource-constrained setups.

2.0 LITERATURE REVIEW

This literature review section establishes the foundational knowledge for the research, focusing on the technology of Digital Twin (DT), Augmented Reality (AR), and the Internet of Things (IoT) in the aquaponics farming system.

2.1 Digital Twin (DT) Technology in Aquaponics Farming System

Digital Twin technology is a dynamic virtual representation of real physical systems, which allows monitoring in a very different yet similar manner to the real physical environment, but also has the possibility of simulating and optimizing those operations. Digital Twin is originally from manufacturing and aerospace; it has arrived in agricultural fields during critical resource-destroying concerns, such as climate variations and the ever-increasing need for improving sustainable practices in its use of crops. By incorporating modelled conditions about the benefits of predictive analytics and scenario simulations, Digital Twins allow farmers to optimize processes and ultimately enhance system performance.

Such tools may be taken as proving that Digital Twin systems give huge opportunities to developers for modelling the behavior of crops under various conditions for future sustainable farming (Pylianidis et al., 2021). Ant then the models would also simulate the impacts of environmental change on crop production and be used by farmers to adopt risk mitigation strategies that in turn increase adaptation to the climate. The complex aquatic-terrestrial habitats required for understanding aquaponics' water quality measurements, plant development, and fish health are likewise modeled by digital twins. (Barricelli et al., 2019)

Applications of Digital Twins for agriculture also include predictive maintenance, whereby models for their virtual alternatives would be used to predict failures in systems and suggest timely actions to avoid service interruptions. Such a prediction was illustrated by Ghandar et al. (2021) by integrating IoT data streams to improve efficiency in an aquaponics system by Digital Twin models. According to the data, it was possible to save about 20% of resources and increase about 15% more in yield, indicating how this technology could be transforming the future.

Apart from improved operational efficacy, digital twins would also promote collaboration among the stakeholders by means of an open real-time visualization so that they are able to assess the performance of the system, conduct risk analyses, and carry out evidence-based interventions. According to researchers (González et al., 2022; Kim & Heo, 2024), digital twins were generated for aquaponics which simulates the current condition of the system to have a better system condition visualization and decision-making onto the system like adding the acid or alkaline solvent to ensure the water pH is suitable for the system.

2.2 Internet of Things (IoT) in Smart Farming

Automated monitoring and control are now being facilitated in agriculture through interconnected sensors and devices from the Internet of Things, which allows farmers to manage their farms remotely from diverse angles. This real-time data collection renders value for action-relevant domain-specific knowledge, such as decision-making for resource optimization within the available means and increased productivity through Internet of Things systems monitoring environmental parameters. An example of this application is the aquaponic system using IoT monitors, which helps with the continuous monitoring of the pH levels of the culture fluid, dissolved oxygen, and temperature, majority to maintain system equilibrium. (Ntulo et al., 2021; Pechlivani et al., 2023)

The functionality of IoT automation is taking farmers' labs upon the shoulders of operations running thousands of miles. In quite a few examples (Karimanzira & Rauschenbach, 2019a; Wang et al., 2020) highlighted that IoT sensors made it possible to monitor aquaponics systems 24 hours a day, thereby realizing a reduction of labour costs by the amount of 30%, while the efficiency of water use improved by 25% as well. It will therefore make it possible to carry out timely interventions to avoid situations such as algal blooms or failure of equipment.

The enhanced scalability of the IoT system adds to its desirability in commercial agricultural endeavors. Now the entire area can be covered by one IoT network to support multiple devices with regard to an understanding of facts over large geographical areas. According to (Hadi et al., 2022; Karimanzira & Rauschenbach, 2019b), analytics related to IoT helped improve productivity in aquaponics through its evident assessment of nutrient deficiencies and subsequent adjustments to input levels. This adaptability forms a critical plan for the future of developed agriculture, which is continuously shifting its focus on the efficient use of limited resources.

2.3 Augmented Reality (AR) in Agriculture

The meaning in a nutshell is that AR makes a bridge between a digital world and a real-world environment by overlaying a user-interactive view on top of objects of the real world, thus enhancing user interaction and making complex data easier to interpret (Li, 2010). This makes it a useful tool in precision agriculture where AR accumulates real-time information with respect to aquaponic applications, such as displaying dynamic information on the system components like a tank and the plants, which can be accessed immediately for insights into operational status.

Researchers (Garzon et al., 2020; Mourtzis et al., 2020) showed that AR interfaces increased user efficiency in system monitoring by 40%, mostly for non-technical users. By displaying critical data, such as nutrient levels and fish health, in an intuitive format, AR diminishes the number of cognitive loads toward quick decision-making. They (Mansor et al., 2024; Yi Chien & Norasri Ismail, 2022) also highlighted the promise of AR in training and education because it allows users to practice system management in virtual simulation before applying it in real life.

Collaboration can be facilitated by AR with remote experts guiding local operators through visual instructions. This is especially useful in aquaponics systems housed in remote areas where access to expert intervention is limited. In addition, this immersion immerses the user and encourages them to adopt new farming technologies.

2.4 Integration of Digital Twin, IoT, and AR

Converging Digital Twin, IoT, and AR technologies as means provides an integrated, holistic method to smart farming. The three things are data-driven insights, real-time monitoring, and intuitive visual access. It is the real-time data feeding into Digital Twin from IoT sensors that forges virtual digital twins, mimicking the current state of physical systems with utmost accuracy. Last but not least, this platform has made it possible for operators to access and react to the often-complicated information with relative ease. They (Ubina et al., 2023) found out that such an unprecedented triadic merger could improve operational efficiency through predictive maintenance, remote monitoring, and real-time interactive system management.

In aquaponics systems, this triplet concept is noted to have prospects for better resource efficiency, reduced downtime, and increased utility satisfaction. (Mourtzis et al., 2020) optimized an aquaponic nutrient delivery system with the application of IoT and AR, leading to an increase in crop yield by 35%. Nevertheless, there are still some barriers to entry, such as high implementation costs and the need for specialists to handle an integrated system. This problem can be solved through concerted efforts from technology developers, policymakers, and stakeholders in agriculture to make the technology less expensive and user-friendly. However, the increasing acceptance of open-source tools and cloud-based platforms might be viewed as a promising trend for their broad use in the future.

3.0 METHODOLOGY

This study employs a mixed-method approach to evaluate the effectiveness and user satisfaction of the existing Digital Twin Interactive Augmented Reality (DTAR) system for aquaponics IoT. The methodology includes a questionnaire-based survey to gather quantitative and qualitative feedback from respondents. The collected data aims to assess user satisfaction, usability, and perceptions of the system's impact on enhancing data visualization, real-time monitoring, and decision-making processes.

3.1 Research Design

A descriptive case study design was adopted to investigate the current DTAR system in detail. This design allows for an in-depth exploration of user experiences and opinions, providing insights into areas of improvement. The study focuses on identifying how well the system meets the needs of its users and its effectiveness in facilitating aquaponics management.

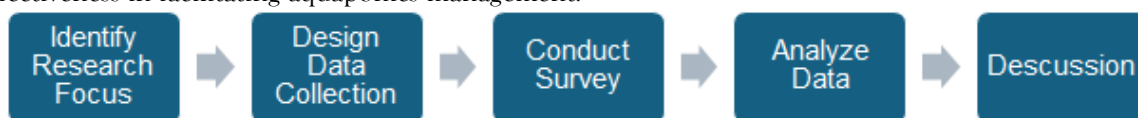


Figure 3.0 Research Design Diagram

Figure 3.0 shows the research design flow diagram. It was systematically defined to evaluate the usability and effectiveness of the actual DTAR system. The process started with focus identification, which needed to be understood and directed toward user satisfaction assessment, usability, and improvement in the convenience of aquaponics management and its evaluation. It was followed by structured data collection instruments implemented through a Google form questionnaire. The survey contained items that utilized the Likert scale to quantitatively measure user satisfaction as well as open-ended questions for qualitative measurement of user experiences and suggestions.

After the survey was carried out, mixed methods were used in analyzing the gathered data. Quantitative responses were analyzed statistically to ascribe levels of satisfaction, while qualitative responses were analyzed with thematic analysis to obtain themes and lead ideas. The culminating stage of the analysis involved interpreting results to generate actionable insights and recommendations toward improving the usability of the DTAR system and effectively confronting user feedback. This way of assessment ensured a comprehensive evaluation of the system.

3.2 Respondents

The respondents were selected using a purposive sampling method, targeting individuals with direct or indirect experience in aquaponics or interest in technology-assisted agricultural systems. The sample included young generations, the age group from 19 to 27 years old, to capture diverse perspectives. A total of 50 respondents participated in the survey, ensuring a sufficient dataset for meaningful analysis.

3.3 Data Collection Instrument

A structured questionnaire was developed to collect data on user opinions and feedback regarding the Digital Twin Augmented Reality (DTAR) system for IoT aquaponics. The questionnaire consisted of the following sections:

- **Demographics:** This section provided insight into the age distribution of respondents.
- **Prior AR Experience:** This section is to gauge their familiarity with augmented reality, which could influence their expectations and feedback.
- **AR Preferences:** This section is to determine user preferences for the type of AR technology employed.
- **Key Features:** To understand user priorities and allow respondents to highlight the attributes they value most in an AR system.
- **Open-Ended Feedback:** This section provided respondents with the opportunity to share detailed feedback or recommendations for improvement.
- **Pricing Expectations:** Participants were asked to assess user expectations on affordability and value in this section.

The questionnaire was distributed online using Google Forms, like Figure 3.1, to maximize accessibility and convenience, ensuring a broad range of respondents could participate and provide meaningful feedback after the respondents used the current application or went through the demonstration of the system.

The image shows a Google Form interface. At the top, the title is "Digital Twin Interactive Augmented Reality in Aquaponics IoT System -- Initial Experiment". Below the title is a "Form description" field. The first question is "Email *", with a sub-label "Valid email" and a note "This form is collecting emails. Change settings". The second question is "What is your age?", with a sub-label "Short answer text". The third question is "Have you had any prior experience with AR technology? *". The form is displayed on a light purple background with a navigation bar at the top containing "Questions", "Responses", and "Settings".

Figure 3.1 Google Forms for collecting feedback

3.4 Procedure

The assessment research methodology for the DTAR system was based on a proper research workflow, which is illustrated in Figure 3.1. The process opened with an engagement of selected respondents, then guided through a well-expanded demonstration of the DTAR system. This was to make sure that all the participants had a good grasp of the system before they could provide their responses. At the induction, were introduced main features of the system such as immediate aquaponics parameters monitoring, virtual 3D experience of the aquaponics environment, and interactive data representation, allowing the respondents to see, interpret, and interact with system outputs.

After the demonstration, participants were invited to fill in a questionnaire that measures their perception of the DTAR system regarding usability, interaction quality, clarity of use, and the overall experience.

In order to ensure a good validity of their responses, the evaluation took place during an organized, well-structured environment, devoid of distractions shown in Figure 3.2. It was organized in such a way that each respondent could visualize the demonstration clearly and would comfortably fill out the questionnaire without distractions. Adherence to ethical standards was also maintained; all respondents were provided complete information about the study; anonymity was kept, in addition to gaining informed consent before engagement.

Besides appearing to provide the procedural and structural overviews, it goes without saying that the inclusion of Figure 3.3 provides the actual interface flow viewed by the respondents during the demonstration. This figure contextualizes the respondent's experience by visually contrasting the various

system features being discussed. Thus, the figure enhances the explanation of the user experience and undergirds transparency by showing the type of content the respondents were engaging with during the evaluation.

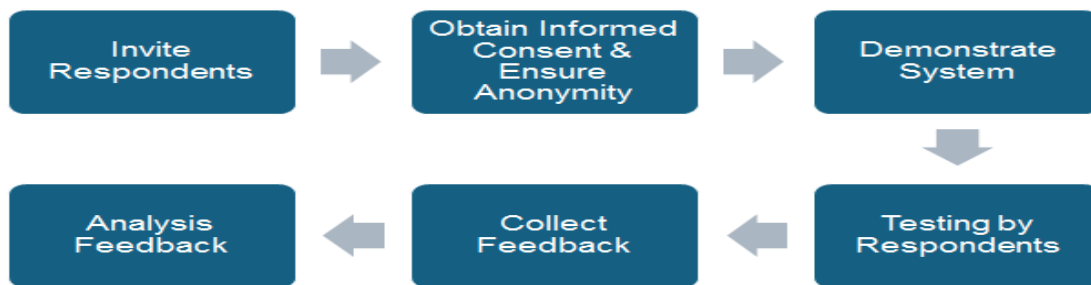


Figure 3.2 Research Procedure Diagram

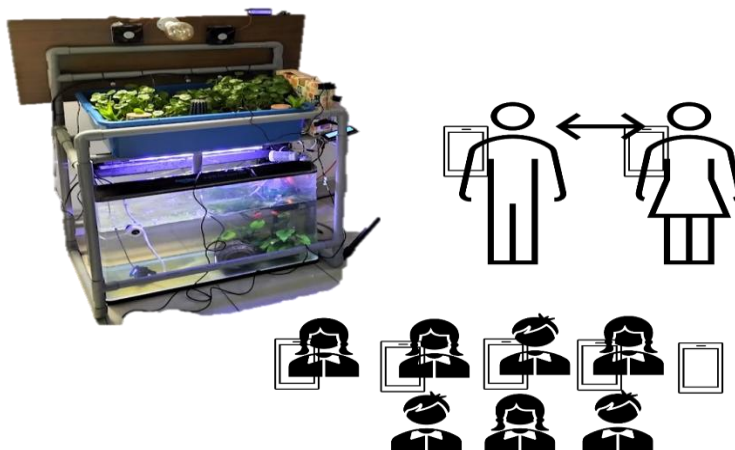


Figure 3.3 Research Experiment Structure Diagram

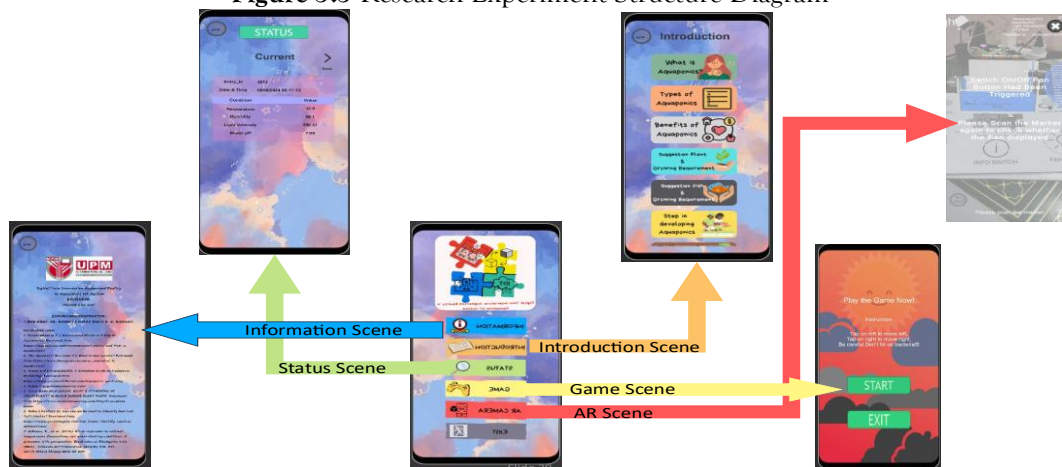


Figure 3.4: DTAR System Interface Snapshot

3.5 Data Analysis

The collected data has been analyzed through a mixed-method approach for an extensive evaluation of the DTAR system, which uses IoT technology for real-time aquaponics monitoring.

- **Quantitative Analysis:**

- With the use of appropriate statistical techniques, responses to closed-ended questions were worked out with the aim of developing metrics such as mean scores, standard deviations, and distributions of an individual's responses across conditions. Such analysis provided more understanding in the areas of user satisfaction, usability, and preferences of AR features and price expectations.

- **Qualitative Analysis:**

- Thematic analysis was conducted for open-ended responses to identify common themes, suggestions from users, and areas of improvement. The analysis highlighted subjective experiences based on how

the DTAR system enables IoT-based real-time monitoring, data visualization, and decision-making in aquaponics systems.

By using qualitative metrics combined with quantitative ones, the mixed-methods approach gave a comprehensive understanding of the perceptions, preferences, and satisfaction levels of users with the DTAR system. Thus, it made sure that both quantifiable results and subtle user feedback were effectively taken care of.

4.0 RESULTS

This section presents the findings from the questionnaire-based survey conducted to evaluate user satisfaction, preferences, and usability of the Digital Twin Interactive Augmented Reality (DTAR) system integrated with IoT for aquaponics. The analysis emphasizes quantitative metrics based on user responses and their preferences for AR features in this context.

4.1 Quantitative Analysis

The data collected through the questionnaire were analyzed quantitatively, focusing on the responses to closed-ended questions related to user demographics, experience with AR technology, preferences for AR features, and overall system usability. The findings are summarized below:

1. Demographics:

What is your age?

50 responses

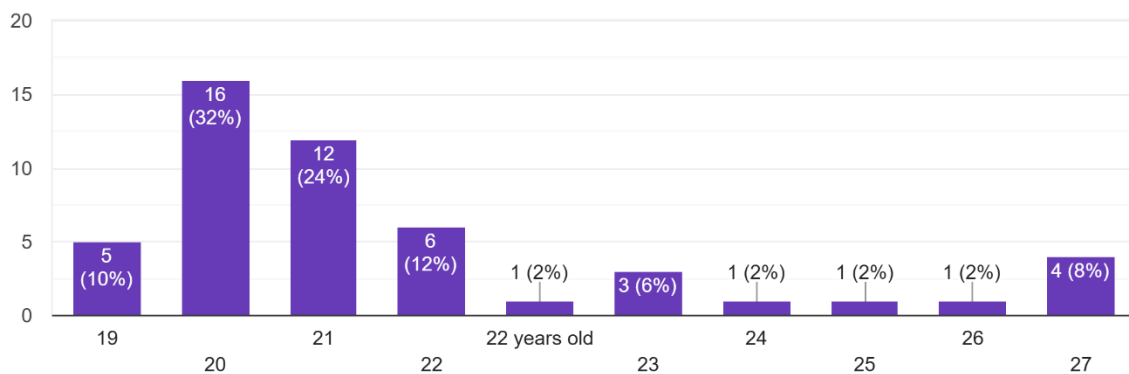


Figure 4.0 Demographic Bar Graph

Figure 4.0 Demographic bar graph shows the ages of the 50 respondents; it is clear from the data that there is a majority of younger respondents in the age group sample. The greatest proportion is 20 years old, comprising 32% (16 respondents), followed by 21 years old at 24% (12 respondents). The respondents had an age range of 19 to 27 years, with a greater concentration in the older brackets. For example, 19-year-olds made up 10% (5 respondents), while 22-year-olds made up 12% (6 respondents). Participants aged 23 constitute 6% (3 respondents), while those aged 24, 25, and 26 each represent 2% or 1 respondent per age. Last of all, 27-year-olds include 8% (4 respondents). This distribution indicates that the respondents are mostly college or university students since they lie on a crowded pattern around ages 20 and 21.

2. Prior AR Experience:

Have you had any prior experience with AR technology?

50 responses

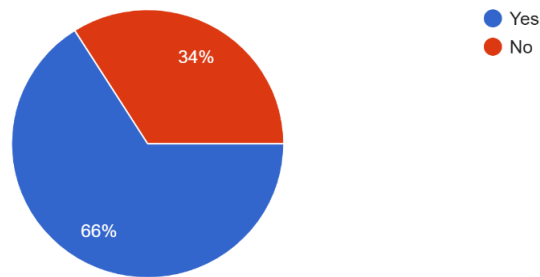


Figure 4.1 Prior AR Experience Pie Chart

Figure 4.1 The Prior AR Experience pie chart shows that 66% (33 people) of the 50 respondents had prior experience with AR technology, while 34% (17 people) had no experience, indicating a strong familiarity with AR in the surveyed group.

3. AR Preferences:

Which type of Augmented Reality (AR) you prefer for this Digital Twin Interactive Augmented Reality in Aquaponics IoT System?

50 responses

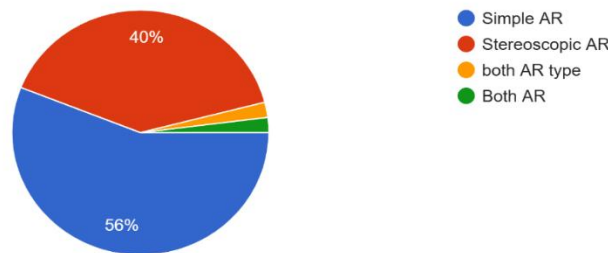


Figure 4.2 AR Preferences Pie Chart

Figure 4.2 AR Preferences pie chart depicts the respondents' preferences for the Digital Twin interactive AR in Aquaponics IoT Systems, which is 50 participants in total. Simple AR was shown to be the most favorable type, with 56%, or 28 people, preferring it, as compared to Stereoscopic AR with 40%, or 20 people. Only a small minority, about 4%, which is 2 people, preferred both types. It shows that the respondents truly favor Simple AR as a means of implementing AR in aquaponic systems.

4. Important Features:

What features do you find most important in an AR application? (Select up to 3)

50 responses

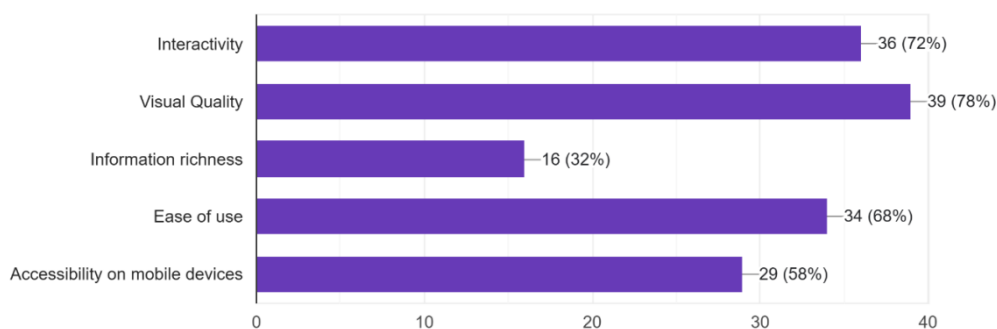


Figure 4.3 Important Features Horizontal Bar Graph

As shown in Figure 4.3 Important Features Horizontal Bar Graph, the most essential characteristics of the AR application are surveyed on the samples of 50 individuals who have chosen a maximum of three answers. The first reason that mattered most to people was Visual Quality, which was selected by 78% (39 participants), followed by Interactivity, chosen by 72% (36 participants). Ease of Use ranked third with 68% (34 participants). Accessibility on Mobile Devices is valued by 58% (29 individuals), and Information Richness is the least chosen feature at 32% (16 individuals). This shows clear favoritism by

users of applications that are visually attractive and interactive compared to those with high information density.

5. Additional Feedback:

Any additional comments or suggestions regarding AR in aquaponics?

15 responses

- it is nice
- interesting
- Really love the Ar model animation .it is very interactive.Stereoscopic Ar would be a new way to unlock the solutions to future problems.
- it is understandable
- good and interesting
- very interesting
- User-Friendly
- add more details for the images that appeared
- no additional

Figure 4.4 Additional Feedback Diagram

50 respondents were targeted for the study, but only 15 gave any comments or suggestions regarding the AR in aquaponics, as shown in Figure 4.4, Additional Feedback Diagram. Most of the comments were positive feedback, praising the interesting, user-friendly design of the system. One of the respondents suggested adding a stereoscopic AR in the future to improve the interactive AR model animation. Some wanted more detailed image information, while others said, "nice" and "understandable." The remaining 35 respondents gave no comments or suggestions. Overall, feedback suggests satisfaction with the current use of AR while indicating further areas for improvement.

4.2 Qualitative Analysis

The open-ended responses provided qualitative data that were rich in insights regarding users' experiences with aquaponics IoT in relation to the DTAR system. Out of the 50 respondents, only 15 gave extensive remarks or recommendations, which were analyzed thematically.

- **Positively received**

User experience surveys show general positive reactions from users regarding the system. Most praised the friendliness and interactivity of the system. The AR model animations received a recommendation from many people, or most of the users, where one user even commented, saying, "an innovative way to understand aquaponics operations." It was referred to as "intuitive and easy to navigate", indicating that it was also an overall experience.

- **Suggestions for Improvement**

Some users have given constructive criticism on the areas for improvement of the system. Most comments would suggest including detailed image information that would build a better understanding of aquaponics components. One commenter, in particular, suggested going with a stereoscopic AR on the premise that this might solve future needs and provide an even more natural experience.

- **Neutral Responses**

Of the 50 participants, 15 commented on the system, while the remaining 35 gave no other comments or suggestions. This just shows a neutral response, which may mean general satisfaction but calls for further interaction to bring out more specific opinions from the users.

The qualitative analysis presents the main strengths of the DTAR system in terms of usage and interactivity-while areas of improvement required from the system, such as image details and possibly more advanced AR features, have also been articulately pointed out.

4.3 Summary of Results

The results depict that the Digital Twin Interactive Augmented Reality (DTAR) facility for aquaponics IoT bears high appreciation levels from users. Quantitative findings show that the respondents are very satisfied with the usability, effectiveness, and visualization of the real-time interactive data. To a greater extent, every other participant concurred that this system is not difficult to use and promotes efficient and enhanced decision-making in aquaponics.

Thus, it was not surprising to receive qualitative feedback that was in tandem with the findings about the system's interactivity and clarity of visualization, while the AR engagement features attracted smooth user comments, with some users appreciating the system for giving them a good understanding of how aquaponics operates. A few minor improvements were suggested, including adding more descriptive pictures and researching stereoscopic AR for a better immersive experience.

In summary, the DTAR system is pretty much effective, fair enough to users, and meets most expectations of users. The feedback also stated windows that would refine the system in terms of offering more visual detail about the product and state-of-the-art AR technologies in increasing user satisfaction and devotion.

5.0 DISCUSSION

The evaluation for Digital Twin Interactive Augmented Reality (DTAR) for aquaponics IoT showed that most user expectations on usability, effectiveness, and interactivity are met. The satisfaction is notably high regarding the ease of use and real-time data visualization, which indicates that the solution advances well in addressing the main challenges in aquaponics management and provides users with a more intuitive and informative experience.

A major strength of the system was in the aspects of real-time monitoring and 3D data visualization, which received great appreciation from the users. This shows that the system has improved the decisions based on live data significantly. Furthermore, the clear preference declared for Simple AR and the high rating given for ease of use indicate that the users are more inclined to prefer systems simple and very easy to navigate.

There, however, were some propositions for improvements from users despite the many bright sides of the system. The suggestions include enhancing the level of detail in images and exploring more advanced AR features like stereoscopic AR for a more immersive and aesthetic appeal of the system, with these improvements being much more likely to solve some user limitations more substantially concerning the information depth and the overall quality of visualizations.

The feedback from the research collection indicates further that a good majority of the respondents had prior experience with augmented reality technology, and it seems that DTAR is dedicated to a tech-savvy audience.

The audience is thus more likely to be comfortable regarding any application on augmented reality and would be one of the possible user demographics for future deployment.

In the end, while the effective as well as appreciated DTAR system for aquaponics IoT has room for further improvements, one area of improvement appears to be in enhancing visual detail and exploring more applications for other types of AR technologies that would use the system. This research should extend to the long-term evaluation of users' interface with the system and recommend ways of widening access to more users.

6.0 CONCLUSION

The Digital Twin Interactive Augmented Reality (DTAR) displays aquaponics IoT as a system that interacts with real-time monitoring with interactive visualization. The convenience of usage provided, enhanced decisional ability, and a superlative level of approval, which indicates that the applicants consider the system as effective in meeting their needs. Real-time data visualization and ease of use were key attributes recognized and positively sensitized toward the possibilities of AR-powered change in aquaponics management.

However, it is still done in areas where improvements may come from. Comments received from users include a lack of realistic visualizations and the need to implement a new form of Augmented reality, such as stereoscopic, so that the immersive experience will be complemented. Such improvements could also address the diverse needs of aquaponics practitioners in gaining wider acceptance of the system.

Long-term research perspectives would include user engagement with the system over time to discover emerging new needs and challenges. The DTAR will also undergo comparative testing against alternative management of aquaponics systems as an effective benchmark to assess its performance and effectiveness. Apart from that, more effort will be needed to develop cost-effective deployment strategies to ensure that other smallholder farmers and resource-poor users can access the system. Enhancing visual features, like advanced AR capabilities like stereoscopic AR, will also improve the user experience and engagement. With these points addressed, the DTAR system may become a more comprehensive and accessible solution that fosters innovation and sustainability in aquaponics.

REFERENCES

1. Bambhaniya, I., Kamleshbhai, B. P., & Bajaniya, V. C. (2003). *Unlocking Sustainable Agriculture: Aquaponics system*. Dimension In Agricultural Sciences: A Way Forward For Sustainability, October.
2. Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A survey on digital twin: Definitions, characteristics, applications, and design implications. *IEEE Access*, 7(M), 167653–167671. <https://doi.org/10.1109/ACCESS.2019.2953499>
3. Garzon, J., Baldiris, S., Acevedo, J., & Pavon, J. (2020). Augmented reality-based application to foster sustainable agriculture in the context of aquaponics. *Proceedings - IEEE 20th International Conference on Advanced Learning Technologies, ICALT 2020*, 316–318. <https://doi.org/10.1109/ICALT49669.2020.00101>
4. Ghandar, A., Ahmed, A., Zulfiqar, S., Hua, Z., Hanai, M., & Theodoropoulos, G. (2021). A decision support system for urban agriculture using digital twin: A case study with aquaponics. *IEEE Access*, 9, 35691–35708. <https://doi.org/10.1109/ACCESS.2021.3061722>
5. González, J. P., Sanchez-Londoño, D., & Barbieri, G. (2022). A Monitoring Digital Twin for Services of Controlled Environment Agriculture. *IFAC-PapersOnLine*, 55(19), 85–90. <https://doi.org/10.1016/j.ifacol.2022.09.188>
6. Hadi, M. S., Sihombing, Y. P., Mustika, S. N., Mizar, M. A., Lestari, D., & Izhar, C. A. A. (2022). Aquaponic Plant Control and Monitoring System Using Iot-Based Decision Tree Logic. *Proceeding - 6th International Conference on Information Technology, Information Systems and Electrical Engineering: Applying Data Sciences and Artificial Intelligence Technologies for Environmental Sustainability, ICITISEE 2022*, 705–710. <https://doi.org/10.1109/ICITISEE57756.2022.10057752>
7. Karimanzira, D., & Rauschenbach, T. (2019a). Enhancing aquaponics management with IoT-based Predictive Analytics for efficient information utilization. *Information Processing in Agriculture*, 6(3), 375–385. <https://doi.org/10.1016/j.inpa.2018.12.003>
8. Karimanzira, D., & Rauschenbach, T. (2019b). Enhancing aquaponics management with IoT-based Predictive Analytics for efficient information utilization. *Information Processing in Agriculture*, 6(3), 375–385. <https://doi.org/10.1016/j.inpa.2018.12.003>
9. Kim, S., & Heo, S. (2024). An agricultural digital twin for mandarins demonstrates the potential for individualized agriculture. *Nature Communications*, 15(1). <https://doi.org/10.1038/s41467-02445725-x>
10. Li, Y. (2010). Augmented Reality for remote education. *ICACTE 2010 - 2010 3rd International Conference on Advanced Computer Theory and Engineering, Proceedings*, 3, V3-187-V3-191. <https://doi.org/10.1109/ICACTE.2010.5579661>
11. Mansor, M., Sulaiman, S., Wahid, R. A., Khan, S. B. O., Ariffin, A. H., & Shaberi, A. H. A. (2024). AR-Speaking Buddy: Designing Content and User Interface of An Augmented Reality (AR)-Based Application for Malaysian Children Speaking Practice. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, 35(2), 57–68. <https://doi.org/10.37934/araset.35.2.5768>
12. Menon, P. C. (2020). IoT enabled Aquaponics with wireless sensor smart monitoring. *Proceedings of the 4th International Conference on IoT in Social, Mobile, Analytics and Cloud, ISMAC 2020*, 171–176. <https://doi.org/10.1109/ISMAC49090.2020.9243368>
13. Mourtzis, D., Siatras, V., & Angelopoulos, J. (2020). Real-time remote maintenance support based on augmented reality (AR). *Applied Sciences (Switzerland)*, 10(5). <https://doi.org/10.3390/app10051855>
14. Ntulo, M. P., Owolawi, P. A., Mapayi, T., Malele, V., Aiyetoro, G., & Ojo, J. S. (2021). IoT-Based smart aquaponics system using arduino uno. *International Conference on Electrical, Computer, Communications and Mechatronics Engineering, ICECCME 2021*, October, 1–6. <https://doi.org/10.1109/ICECCME52200.2021.9590982>
15. Pechlivani, E. M., Papadimitriou, A., Pemas, S., Ntinias, G., & Tzovaras, D. (2023). IoT-Based Agro-Toolbox for Soil Analysis and Environmental Monitoring. *Micromachines*, 14(9). <https://doi.org/10.3390/mi14091698>
16. Pylaniadis, C., Osinga, S., & Athanasiadis, I. N. (2021). Introducing digital twins to agriculture. *Computers and Electronics in Agriculture*, 184. <https://doi.org/10.1016/j.compag.2020.105942>
17. Reyes Yanes, A., Abbasi, R., Martinez, P., & Ahmad, R. (2022). Digital Twinning of Hydroponic Grow Beds in Intelligent Aquaponic Systems. *Sensors*, 22(19). <https://doi.org/10.3390/s22197393>
18. Ubina, N. A., Lan, H. Y., Cheng, S. C., Chang, C. C., Lin, S. S., Zhang, K. X., Lu, H. Y., Cheng, C. Y., & Hsieh, Y. Z. (2023). Digital twin-based intelligent fish farming with Artificial Intelligence Internet of Things (AIoT). *Smart Agricultural*

- Technology, 5. <https://doi.org/10.1016/j.atech.2023.100285>
19. Verdouw, C., Tekinerdogan, B., Beulens, A., & Wolfert, S. (2021). Digital twins in smart farming. *Agricultural Systems*, 189(January), 103046. <https://doi.org/10.1016/j.agsy.2020.103046>
20. Wang, S. C., Lin, W. L., & Hsieh, C. H. (2020). To improve the production of agricultural using IoT-based aquaponics system. *International Journal of Applied Science and Engineering*, 17(2), 207–222. [https://doi.org/10.6703/IJASE.202005_17\(2\).207](https://doi.org/10.6703/IJASE.202005_17(2).207)
21. Yi Chien, L., & Norasri Ismail, M. (2022). Development of Mobile Application for Applying Aquaponics Techniques in Farming Using Augmented Reality Approach. *Applied Information Technology And Computer Science*, 3(2), 591–610. <https://doi.org/10.30880/aitcs.2022.03.02.037>