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AQUAPONICS: A serious game to promote aquaponics systems for local community development

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ABSTRACT

The contributions of food production in aquaponic systems to the Sustainable Development Goals favor sustainable development. However, migrating from a traditional farming system to an alternative one requires a technology appropriation process involving initial recognition of its functioning. However, conventional education has not effectively transmitted this knowledge, especially in contexts other than formal education. Therefore, in this study, a serious board game was developed as a pedagogical strategy to increase the awareness and understanding of aquaponic food production of the general public and enhance sustainability practices in developing communities. The game board was designed with elements that facilitate the gaming experience for people with color blindness. The study was conducted in Colombia, and it included 1,096 people from 23 municipalities. For the analysis, four game groups were considered: young people, adults, elders, and a mixed team of participants of all age groups. The variables observed were the duration and number of attempts to win the game. A categorical principal component analysis (CATPCA) was used to analyze the correlation between the variables of the set of observations. The results show that the participants could recognize elements and the basic functioning of an aquaponics system. Furthermore, the experience gained during the game promotes cooperation in problem-solving and the motivation to continue learning, contributing to spreading the technology in communities.

1. Introduction

Sustainable development involves changes in the way resources are used, which consists of the development of new technologies and institutional changes to meet the current and future needs of people (Brundtland, 1987). Adopting sustainability is imperative, and a growing number of higher educational institutes are developing tools and new teaching methods that contribute to knowledge transfer as well as the social appropriation of new technologies (Stanitsas et al., 2019) from individual and community approaches (Bevilacqua et al., 2015).

However, education for sustainable development is not yet widespread and is not always effective through conventional means (Chappin et al., 2017). In this sense, Stanitsas et al. (2019) proposed that serious games represent one of the best means to engage in learning about sustainability. Serious games are part of game-based learning; they facilitate learning through game content and play and generate spaces for problem-solving through challenges that provide players with a sense of achievement (Krath et al., 2021), enriching the learning experience since it favors the development of skills, as well as the motivation and autonomy to continue learning (Garzón et al., 2020). Likewise, strategy games improve engagement, promote inclusion, and provide a risk-free environment for decision-making, as they allow for exploring unforeseen events and test scenarios (Novotny et al., 2024).

Research related to serious games is often conducted in formal education settings; however, understanding sustainability concerns all individuals regardless of their occupation, age, and educational and income levels. Therefore, the scope of serious games related to sustainability should be directed at a broad general audience (Chappin

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et al., 2017) but also recognize the difficulty associated with the effectiveness of game-based learning (Connolly et al., 2012). In this case, serious games are useful for collecting data on preferences and estimating gaps in contexts where participants may have difficulty with complex content and do not feel entitled to express their concerns due to cultural norms, power asymmetries, and other reasons (Rodela et al., 2019).

Aquaponics is a technology that combines tank aquaculture with hydroponics and involves microbiological processes that transform fish waste or residues into nutrients for plants in a closed water cycle (Baganz et al., 2022; Masabni and Niu, 2022), representing an entrepreneurial opportunity (Goddek et al., 2015) and food sovereignty for communities (Laidlaw and Magee, 2014). This production system contributes to sustainable development mainly to objectives 1, 2, and 6 of the 2030 Agenda of the United Nations (2015). In addition, it improves crop yields and minimizes water use and polluting discharges (Villarroel et al., 2016), producing healthier food without using fertilizers (Joly et al., 2015).

Although globally, foods produced through aquaponics are well accepted by consumers, specific legislation is required to help entrepreneurs formulate business plans aimed at banks and investors (Cammies et al., 2021). In this sense, the "Mission of Wise Men" of the Government of Colombia (Gobierno de Colombia, 2019), i.e., policies for the development of the country were defined, some based on the implementation of technologies based on bioeconomy, and at the local level in the Tolima region (Asamblea Departamental del Tolima, 2022), those that reduce environmental pollution and generate social development such as food production in aquaponics are promoted. In this context, implementing innovative systems such as aquaponics requires entrepreneurs to acquire documentation and technical knowledge on fish and plant production and waste transformation processes by microorganisms (Goddek et al., 2015). However, given the complexity of the operation of these systems, it is necessary to develop strategies for social appropriation of knowledge and technology to achieve conditions of economic sustainability for small producers (Suski et al., 2022), both in rural and urban areas (Rahdriawan and Arriani, 2020). Therefore, it is necessary to promote learning about its functioning and operation, which can contribute to improving the income of entrepreneurs (Love et al., 2015).

Since aquaponics has emerged as a sustainable and resilient community system to improve food security and promote environmental sustainability (Chaher et al., 2024), it is appropriate for teaching in communities and also for consumers who need more information (König et al., 2018), enhancing profitability for small producers (Striani et al., 2023). Therefore, there is a need to increase the provision of education, research, and development to improve aquaponics commercialization (Raulier et al., 2023).

A bibliometric analysis in aquaponics indicates that year-wise citation growth has focused primarily on system performance optimization, wastewater treatment, nutrient management, production systems, technology adoption, and plant and fish varieties (Basumatary et al., 2023). Likewise, a notable increase in research publications on serious games for education (Ozyurt et al., 2024), agriculture (Dernat et al., 2024), and environmental (Ahmadov et al., 2024) and social sustainability promotion (Ahmadov et al., 2024) were identified. Furthermore, to the best knowledge of the authors, no study has used serious games to create learning experiences in developing communities on food production with aquaponics systems, and further research is required to develop empirical evidence that accounts for the added value of game-based learning situations in non-formal education.

On the other hand, the National Eye Institute (2024) reported that approximately 8.33% of the global population has some form of color blindness. In this sense, few games are accessible to visually impaired people (Agrimi et al., 2024), and few studies incorporate elements that improve the identification of shapes and colors in digital tools and games for people with color blindness (Dastan et al., 2024). Therefore, since board games and role-playing games are more common today for learning about agriculture (Dernat et al., 2024), this study describes the development of the board game called AQUAPONICS, which introduces elements that can facilitate performance for players with visual impairments such as color blindness and which is also proposed as a tool to increase the awareness and understanding of the operation and production of food with aquaponics systems in non-formal learning environments for the general public and also to disseminate sustainability concepts and practices that promote sustainable behavior in developing communities, since case studies to promote aquaponics are mainly developed in academic environments (Garzón et al., 2020).

1.1. Study objectives and research questions

The research question of this study is formulated as follows: How effective is the serious game AQUAPONICS in promoting the learning of aquaponics in local community development and enhancing sustainable behaviors? In this context, effectiveness is defined as the number of people who express their desire to learn more about food production in an aquaponics system. This paper addresses whether, through the experience of playing the serious game AQUAPONICS, people with diverse backgrounds achieve a general understanding of the functioning of an aquaponics system in a non-formal education environment. Therefore, derived questions are raised, such as: a) Do people learn about aquaponics production through the game, even if they do not have general knowledge of agriculture or aquaculture?; b) In a non-formal education environment, is it possible to generate motivation towards learning about aquaponics in people of diverse educational levels or professions after having played AQUAPONICS?; c) Is it possible to establish a strong relationship between the time it takes a person to win the game depending on his/her age?

2. Material and methods

2.1. Study area

The study was conducted in the Tolima region of Colombia, which has an area of 23,663 km^2; it is comprised of 47 municipalities and 1.38 million inhabitants, with a Gross Domestic Product (GDP) per capita of USD 6.65M in 2024 (Fig. 1), and an unemployment rate of 14.1% in the capital of Tolima, Ibagué (Ministerio de Comercio, Industria y Ministerio de ComercioIndustria y Turismo, 2024). Likewise, 32.5 % of the population lives in poverty and 9.3 % in extreme poverty, registering a Gini coefficient of 0.511. There is a higher education coverage of 36.0 % (DANE & DIMPE, 2023), and the main economic activities are agriculture and livestock/fishing, which contribute 21.1 % and 8.3 % to the regional and national GDP, respectively.

2.2. AQUAPONICS board game

Considering that learning through playing allows the content of teaching to be adapted to different learning styles, even if the participants have previously been involved with the subject or not (Kerfoot et al., 2012), this study developed a serious board game called AQUAPONICS, focused on problem-solving around feeding a population and the participants face an antagonistic system that is the game itself. The players must make decisions and configure strategies based on their conceptions. Thus, bad decisions result in the impossibility of feeding the entire population. In this sense, the players must develop knowledge that allows them to win or stay in the game, similar to the approach proposed by Sanchez (2019).

2.2.1. Board game goals and story

AQUAPONICS was designed to teach people how to produce food in aquaponics systems. Therefore, the game offers an approach that allows the participants to recognize the three main elements of aquaponics: i)

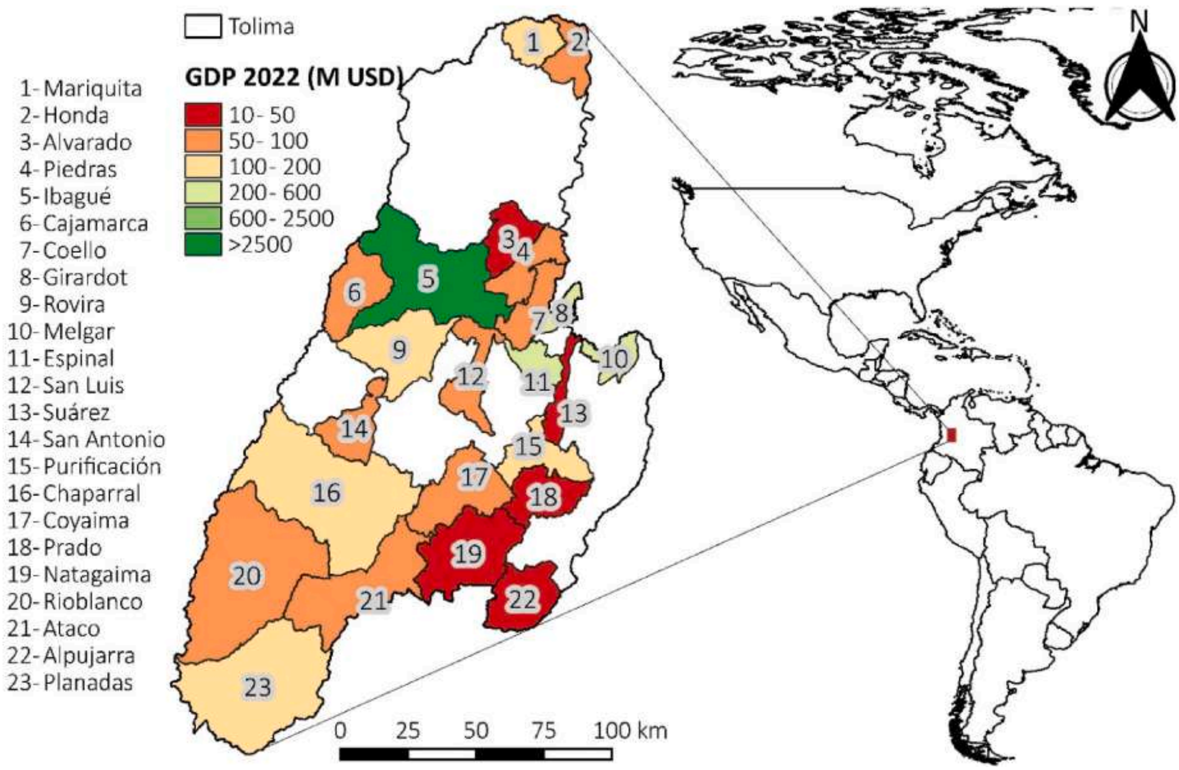

Fig. 1. Study area location and GDP per municipality. Elaborated with data from Ministerio de Comercio, Industria y Ministerio de ComercioIndustria y Turismo (2024).

aquaculture production in tanks, ii) production of vegetables in hydroponics, and iii) the transformation of fish waste into plant nutrients. Functional interrelations of the system were also incorporated to ensure successful food production. AQUAPONICS is a single-player role-playing game that can be played alone or in teams against the game. Therefore, it is not a game based on competition between players; instead, it promotes cooperation so that players can learn from direct or indirect interaction with the game. Each of the five rounds of the game presents a challenge that the participants must overcome. Thus, the participants who overcome all five rounds win the game. On the contrary, they must restart from the first round if they cannot win a round. The game lasts approximately 20–40 min, which is consistent with what was proposed by Hertzog et al. (2014) concerning the duration of role-playing games with a learning approach.

The story or narrative of the game focuses on a community of 100 inhabitants that obtains their livelihood from traditional soil farming. Hence, different environmental hazards occur in each round of the game and systematically prevent further cultivation in the soil. Therefore, the player must migrate food production to an aquaponic system. In each round, the players have a certain amount of money that can be invested in buying seedlings for the hydroponic system, fingerlings for the aquaculture system, energy for the water recirculation system through pumping, and bacteria for the operation of the biofilter that transforms fish waste into nutrients for the hydroponic system. At the end of each round, the players harvest the food produced, and if they manage to feed 100 people, they move on to a new round; otherwise, the players lose the game and must restart from the beginning, i.e., from the first round.

A limited number of options leads the players to win the game, and each one relates to appropriate routes to start food production in an aquaponic system. In this way, AQUAPONICS provides a narrative with clear goals, allowing players to recognize the objectives that must be met in each of the five rounds of the game. This feature contributes to the pedagogical value of the game to the extent that it facilitates the exercise of interpretation for the players regarding the expected performance (Min et al., 2014). Fig. 2 shows a sequence of decisions the players can make in each round to win the game. Thus, once production in the aquaponics system is balanced, the participants will discover that it is possible to produce food for more than 100 people and generate a surplus that represents new income for their community.

2.2.2. Features of the game board

Playing the game requires no high mathematical skills or previous knowledge of aquaponics. The board game is composed of five parts: 1) the hydroponics system on the top left and the fish tanks on the bottom left representing the aquaculture system; 2) a pump for water recirculation and the biofilter with the bacteria located on the same box in the center-bottom left. Relevant information on what the pump and the biofilter with bacteria are used for and what they achieve is located on the top right of the game board; 3) a silo on the top center to store surpluses when more than 100 foods are produced; 4) five lines (columns) of cultivation on land located on the center-right of the board; 5) a calculator to account for the food produced situated on the bottom right (Fig. 3). The layout of the game board offers a complete overview of the aquaponics system so the player can easily recognize each component and functional purpose within the food production process.

The game board design incorporates elements that facilitate information recognition for people with visual impairment, such as color blindness, corresponding to 5 % of the global population. These elements are a) complementary use of figures and icons with text, geometric shapes and contrast with patterns (Buultjens and Ferguson, 1994), b) legible large-sized texts with compensation of RGB (Red, Green, Blue) images to the HLS (Hue, Saturation, Lightness) color space (Ohkubo and Kobayashi, 2008), and c) high contrast application, and more saturated and darker colors (Ribeiro and Gomes, 2019). In this way, the game board facilitates the visual identification and description of each element of the game, which, according to Tanuwidjaja et al. (2014), allows improving the gaming experience for people with color blindness, reducing the visual factors that could interfere with the

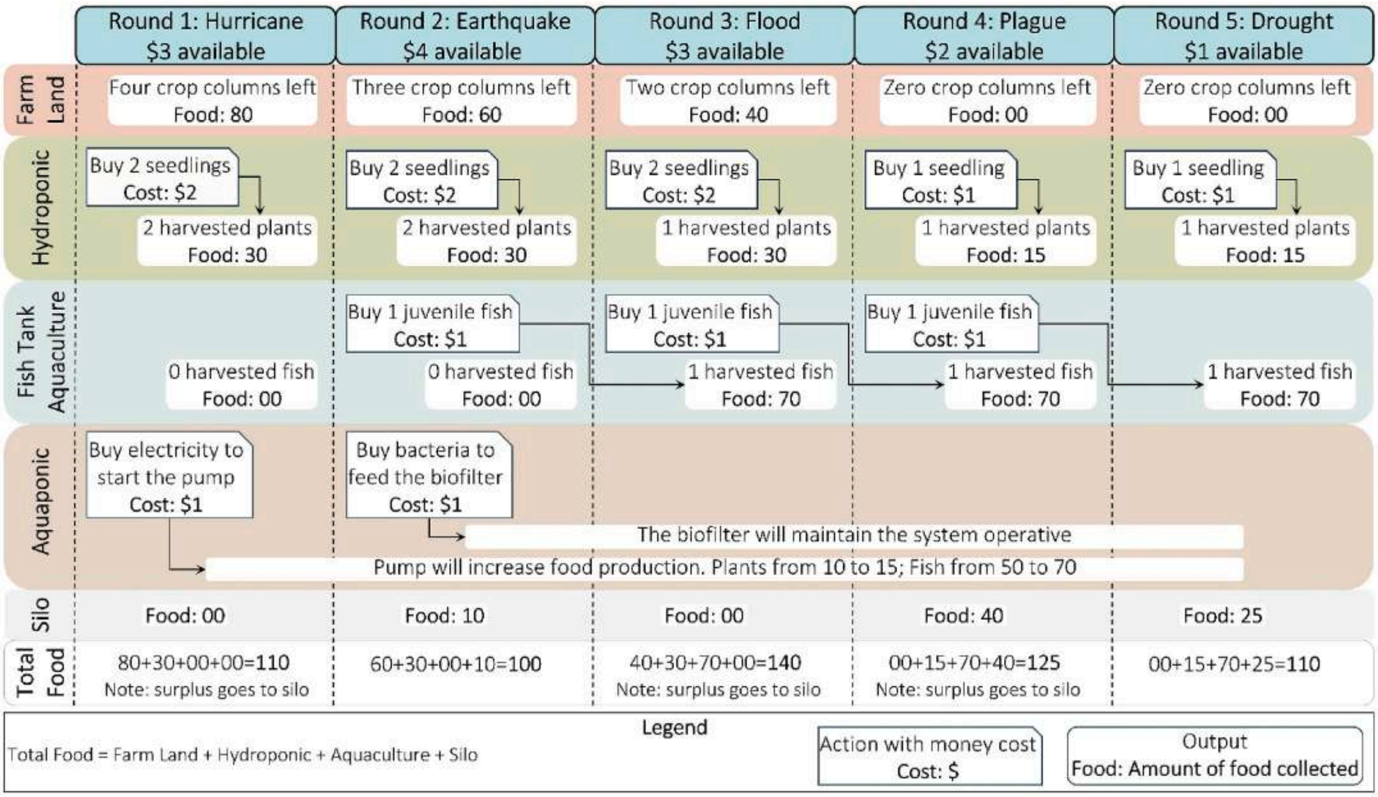

Fig. 2. Example of a sequence of decisions to win the game.

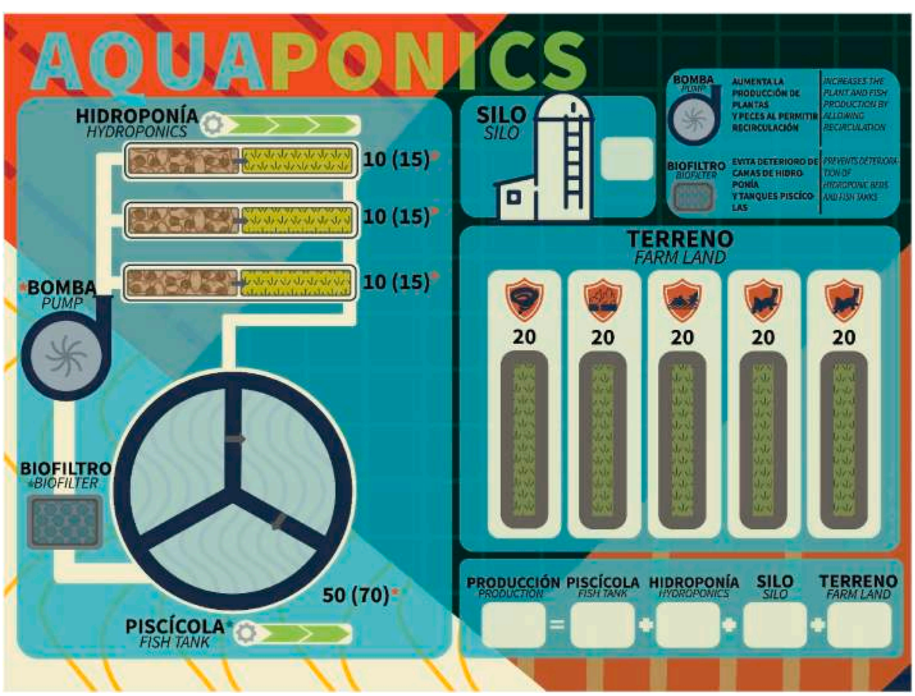

Fig. 3. AQUAPONICS game board.

success of each player (Fig. 3). In this case, each part of the game board is accompanied by titles to complement its identification as proposed by Choi and Chlebek (2024), as well as different and large-sized shapes for each element of the game as suggested by Raynal et al. (2024). Furthermore, as recommended by Jamil and Denes (2024), six highly contrasting game boards in images and text are available in the supplementary material included in Osma et al. (2024). So, in any case, this game provides people with visual impairments with conditions that make it easier for them to play with others and have similar chances of winning, as Agrimi et al. (2024) stated.

2.2.3. *Chromatic simulation of the game board*

Six boards for the AQUAPONICS board game were designed with different color combinations according to the configurations described in section 2.2.2. Thus, 48 tests were conducted with two color blindness vision simulators (Fortin, 2024; Colorlite, 2024) to identify whether it is possible to differentiate texts and game elements by participants who could suffer one of the eight types of color blindness conditions: Protan, Protanomaly, Deutan, Deuteranomaly, Tritan, Tritanomaly, Partial monochromacy, and Monochromacy. The results of the tests allowed the identification of six game-board configurations, allowing the differentiation of the texts and elements of each part of the aquaponics system (Fig. 4).

2.2.4. *Scoring description*

AQUAPONICS is a strategy game that does not rely on randomness, so games can be repeated multiple times for players to adapt their strategies based on decisions made in previous attempts (Seibert and Vis, 2012). This avoids conflict between participants, leads them to learn from their mistakes, and facilitates decision-making in the next game, similar to the Eurogames model (Sousa and Bernardo, 2019). Scoring is, therefore, based on prioritizing the goals defined for each round in the hydroponics and aquaculture systems and their interconnectivity. So, only some sequences of decisions the player makes will lead to winning the game. Similarly, the order in which agricultural practices are chosen is decisive, as previously developed by Jouan et al. (2021). Craven et al. (2017) and Katsaliaki and Mustafee (2013) incorporated climate variability events and anthropogenic pressures into the game. Fig. 2 presents a possible decision sequence that allows the player to collect at least 100 food units in each of the five rounds and win the game.

Fig. 4. Chromatic simulations of the AQUAPONICS game board.

2.3. AQUAPONICS sessions

AQUAPONICS sessions were held in 23 municipalities in Tolima, Colombia (Fig. 1) and 1,096 people over 18 years of age participated voluntarily. The sessions were distributed in single players according to the age of the player or in multiplayer players when a young person, an adult, and an elderly player cooperated (Fig. 5). This configuration allowed young and adult participants to assist the elder (Alpuche Álvarez et al., 2024). Before the start of each game session, the approval of the Institutional Ethics Committee was obtained, and informed consent was attained from all participants.

2.3.1. Data analysis

The Aquaponics Learning Questionnaire (ALQ) was used to record information about the knowledge of participants on aquaponics. It included three qualitative variables (age group, education level, and economic activity), nine dichotomous (Yes/No questions), and two numerical (number of attempts and duration in minutes to win the game) variables (Table 1). GDP values per municipality were also incorporated. The results were analyzed by implementing the categorical principal component analysis (CATPCA) (Linting et al., 2007) using the IBM SPSS Statistics v25 program (Meulman and Heiser, 2013). CATPCA is the nonlinear equivalent of the principal component analysis and facilitates the combination of nominal, ordinal, and numerical variables and the identification of nonlinear relationships between variables (Jamali-Dolatabad et al., 2021). Therefore, it is possible to quantify categorical variables and reduce their dimensionality. Its main functionality is to reduce an original set of variables to a smaller set of uncorrelated variables that represent most of the information found in the original variables (Li et al., 2023). This analysis has been widely used in various areas, such as environmental sciences and education, among others. (e.g. Ellis et al., 2006; Martín-Jaime et al., 2021). Likewise, to determine the representativeness of the sample, the Kaiser-Meyer-Olkin (KMO) sphericity test (Kaiser, 1974) was applied, which was acceptable (KMO = 0.693).

The ALQ incorporated questions at the beginning and end of the game (Table 1) to identify the recognition of elements and operating principles in aquaponics systems by the participants. For this purpose, variables such as age, educational level, economic activity, previous knowledge in any agricultural area, their perception of the clarity, ease, and knowledge the game offers about aquaponics, and their desire to continue learning were defined. Thus, the number of attempts and the

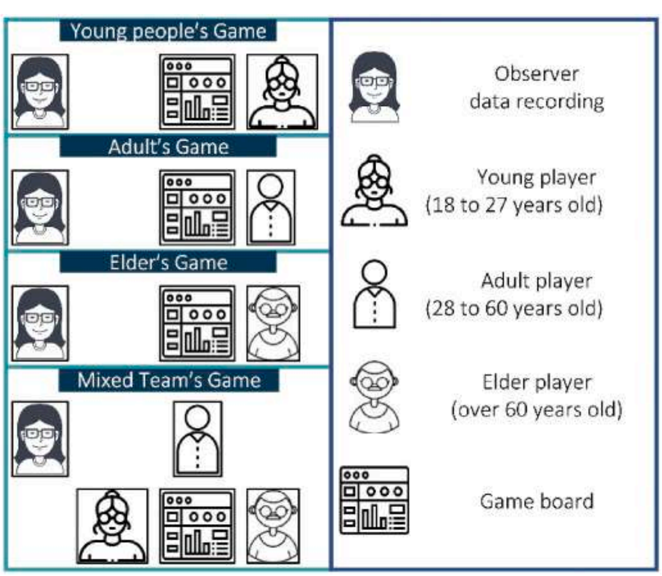

Fig. 5. Groups formed to play the game.

Table 1
Description of the variables of the Aquaponics Learning Questionnaire (ALQ).

Variables collected before playing								Variables observed during the game		Variables collected after playing			
Age group (years old)	Education level	Economic activity	Previous board game experience?	Knowledge of agriculture?	Knowledge of aquaculture?	Knowledge of hydroponics?	Knowledge of aquaponics?	Number of attempts to win the game	Duration to win the game (in minutes)	Were the rules of the game clear?	Was the game easy to play?	Did the game give you a general idea of aquaponics?	Do you want to learn more about aquaponics?
Young people (18–27) Adults (28–60) Elders (over 60) Mixed	Elementary school High school Technician/ Technologist Professional Postgraduate	Agriculture and Livestock Employee Freelancer Retired Unemployed	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Number, integers	Number, rationals	Yes/No	Yes/No	Yes/No	Yes/No

time invested in the game (duration) until achieving the goal of feeding 100 people in each round were measured since these variables are indicators of performance and level of understanding in serious games (Martindale et al., 2024), as well as their ability to solve problems and level of learning (Kang et al., 2017).

2.3.2. Feedback and validation

The game board represents an adaptation of the Single Recirculating AquaPonic System (SRAPS) proposed by Rakocy et al. (2006), built at Universidad de Ibagué, Colombia. Therefore, the operational principles of the SRAPS were simplified and transferred to the AQUAPONICS game. Thus, the situations the player faces are consistent with the operational situations of the real system. In this sense, the authors from Universidad de Ibagué, who were in charge of the aquaponics system operation, were available to offer feedback and validation to the participants after the game experience.

3. Results and discussion

3.1. ALQ responses

A total of 1,096 people from 23 municipalities played AQUAPONICS (Fig. 6a), of which most, i.e., 1,092, won the game. The sessions were conducted with single players, where 36 %, 29 %, and 15 % of the players were adults, young, and elders, respectively, and 20 % were multiplayer sessions, with teams of three players (including a young, an adult, and an elderly participant) (Figs. 5 and 6b). The responses recorded in the ALQ indicate that 60 % of the participants had knowledge of agriculture; the rest had no knowledge related to food production (Fig. 6c). Likewise, 21 % and 15 % of the participants had knowledge of hydroponics or aquaponics, respectively. Thus, despite 85% of participants had no prior knowledge of aquaponics, after the AQUAPONICS gaming experience, more than 85% indicated that the game gave them a general idea of aquaponics, and more than 75 % expressed willingness to learn about this production system. Therefore, this suggests that the board game managed to spark the interest of participants of all ages through interaction with the tangible elements of the game, addressing practical challenges, and individual and group learning, as Charlo et al. (2022) reported regarding learning through playing.

Similarly, Fig. 7 identifies that participants with no agricultural knowledge expressed 23 % less interest in learning about aquaponics than those with knowledge. Meanwhile, over 79 % indicated that AQUAPONICS provides a general idea of aquaponics regardless of their knowledge of different food production systems. Therefore, it is necessary to clarify that the ALQ does not assess the willingness or ability of participants to switch to an aquaponic system. However, AQUAPONICS aims to align its objectives with the immediate needs of participants, especially food sovereignty, to promote technology adoption and contribute to sustainable development. These needs take priority over

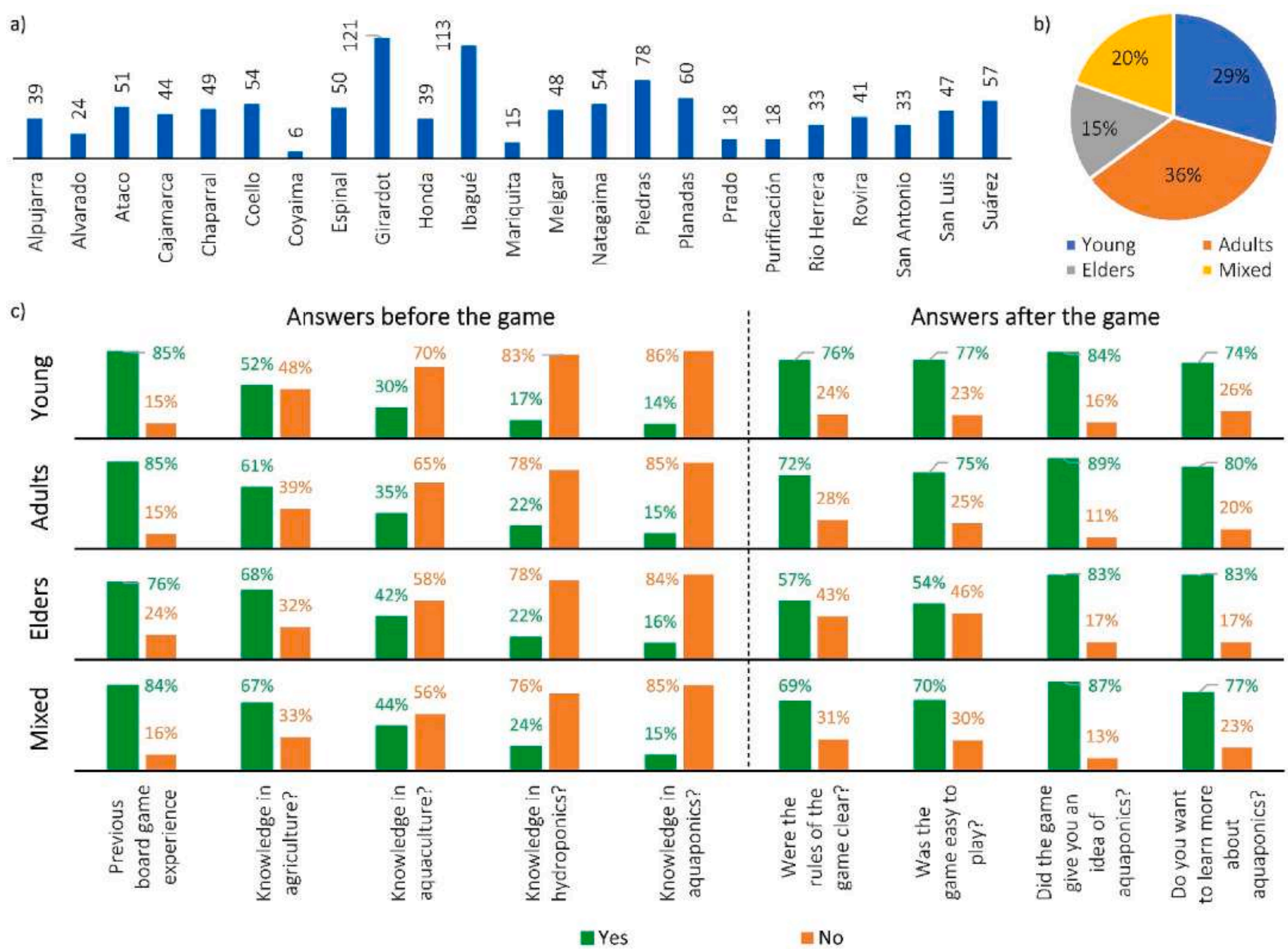

Fig. 6. a) Number of games played per municipality, b) Number of games played per gaming group, and c) responses to the Aquaponics Learning Questionnaire (ALQ) per gaming group.

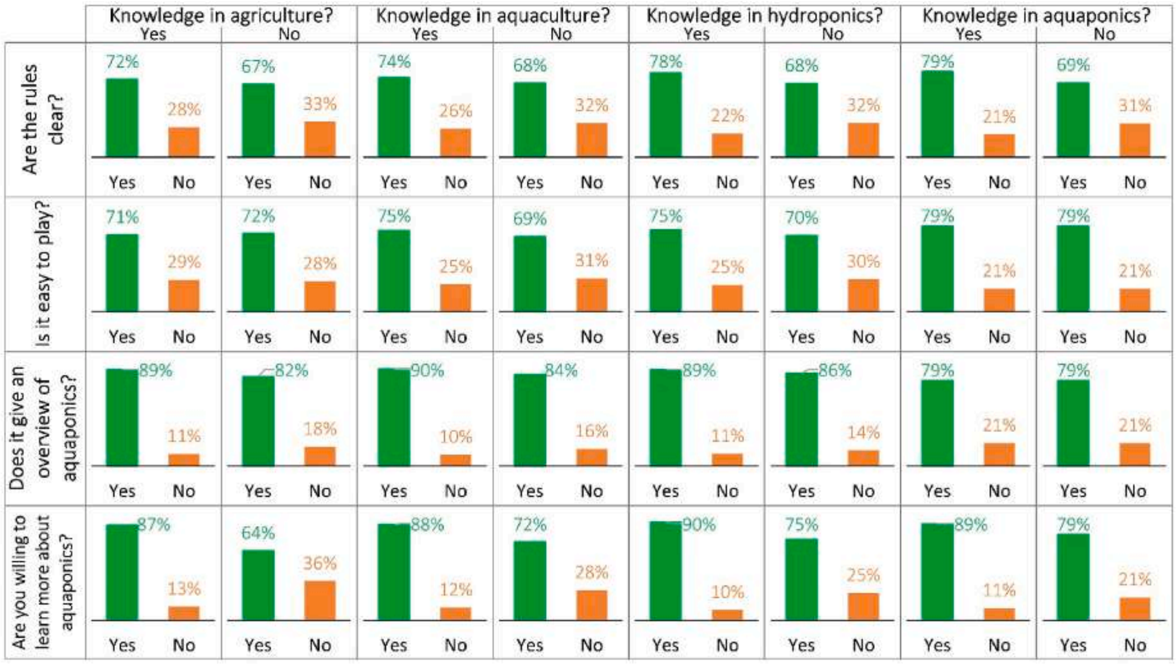

Fig. 7. Responses of participants according to their knowledge of agriculture, aquaculture, hydroponics, and aquaponics.

long-term investments in agriculture and livestock, so addressing these priorities is essential to stimulate greater interest in investing in alternative production systems (Novotny et al., 2024).

3.2. CATPCA and average player performance analysis

The CATPCA analysis shows the variables number of attempts, duration, age, and GDP per municipality and education level as component loadings. In contrast, economic activity and age group were defined as centroids of their object scores. Fig. 8a and b presents the first two principal components of the CATPCA for economic activity and game groups, respectively. For economic activity, duration, and education level, the values for principal component 1 are 0.57 and −0.67, respectively (Fig. 8a). For game groups (young people, adults, elders, and the mixed team), it was 0.63 and −0.56, respectively (Fig. 8b). Therefore, these were the most relevant variables concerning the interpretation for principal component 1 (Carty and Claveria, 2024). The results indicate a strong correlation between the variables duration and number of attempts, an almost independent correlation between the age of players and duration-number of attempts, and an inverse correlation between duration-number of attempts and education level and GDP. This means that participants with higher educational levels tended to win AQUAPONICS in less time and with a lower number of attempts. Similarly, participants in the categories unemployed and agriculture and livestock took more time and number of attempts compared to others (Fig. 8a). Thus, young people developed better performance and level of understanding of the game, considering that, on average, it took them 2.74 attempts and a duration of 21.8 min to win the game, in contrast to adults who required 2.23 and 2.66 % more attempts and duration, and similarly with the elders who registered 20.07 and 12.52 % more attempts and duration compared to young people (Figs. 8b and 9b). However, the results of the CATPCA explained between 50.1 and 56.7 % of the data set, so the influence of the high variance of the variables analyzed that the model could not explain was identified (Márquez et al., 2021). Overall, the CATPCA allowed to identify relationships between the sets of variables and their relationship with the duration and number of attempts. The results indicate independent trends in relation to the variables used (Fig. 8c). Therefore, the learning outcomes of the game could be achieved independently of the economic, cultural, or age aspects of the participants (Meershoek et al., 2014).

In this regard, the average performance of the players in terms of duration and number of attempts to win in AQUAPONICS is presented in

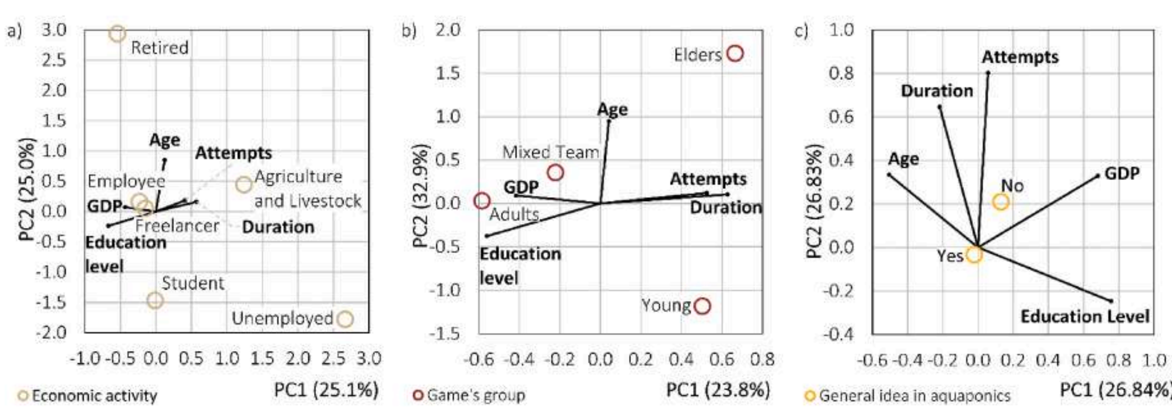

Fig. 8. a) CATPCA of the agriculture, aquaculture, hydroponics, and aquaponics learning questionnaire (ALQ) with economic activity as centroid, b) CATPCA of the ALQ with gaming group as centroid. c) CATPCA of the ALQ with a general idea in aquaponics as centroid.

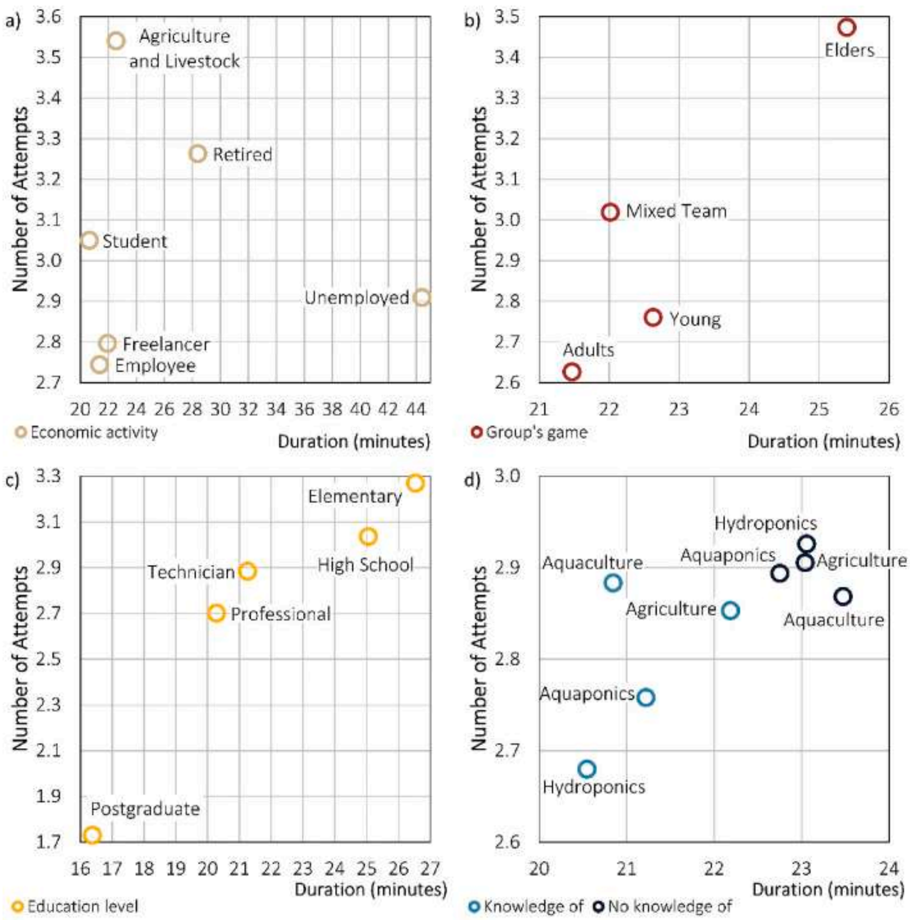

Fig. 9. Average game duration and number of attempts to win the game according to a) economic activity, b) game group, c) education level, and d) previous experience in agriculture, aquaculture, hydroponics, and aquaponics.

Fig. 9, where unemployed participants, on average, took longer to win the game. Further, participants in the agriculture and livestock categories made more attempts compared to others with alternative economic activities (Fig. 9a). Similarly, depending on the game group, elders needed more time and more attempts to complete the objectives; on the other hand, adults recorded better performances (Fig. 9b), consistent with what was reported by Cross et al. (2023) who found that adults are better board game players. In this sense, an inverse relationship was identified between the level of education and the duration and number of attempts required for players to win the game (Fig. 9c), which, according to Chappin et al. (2017), is related to the level of understanding of sustainability. Players with knowledge of other food production systems took less time and number of attempts to win the game compared to those who did not have the knowledge. However, those with knowledge of hydroponics had the best performance compared to the other groups analyzed (Fig. 9d). In general, it took the participants less than 25 min to win the game, except for players in the categories retired, unemployed, elder, and elementary school who took longer time to win the game. This is consistent with what was reported by Gordon and Yiannakoulias (2020) who identified that a 20-min gameplay duration is associated with a pleasant experience for the player.

In this context, game time or duration and attempts are not only metrics of persistence but correspond to indicators of an iterative cycle of trial and error that fosters the development of specific competencies such as decision-making and problem-solving (Lei et al., 2022). As aquaponics players repeat actions and decisions within the game, they adjust their strategies in response to the feedback the game provides in its narrative. This is consistent with experiential learning theories, which emphasize the importance of deliberate practice and reflection to consolidate knowledge or a skill (Dahalan et al., 2024).

3.3. *Debriefing session with the players*

Learning can occur during game-related activities; however, during debriefing, players relate their experiences to actions performed in the game (Novotny et al., 2024), allowing for deeper levels of understanding (Gugerell and Zuidema, 2017). Although another study recorded a more extended debriefing time of 4-h game sessions (Novotny et al., 2024), in this study, the debriefing took place after the participants won the game. Unfortunately, the debriefing was brief, given the limited time available the participants had due to their occupations (Alpuche Álvarez et al., 2024) and the number of participants in each municipality. In this sense, AQUAPONICS aimed to promote aquaponics systems to a broad public through the game, similar to what was proposed by Khoury et al. (2023). Consequently, a total of 470 comments were received, among which 57 people indicated that AQUAPONICS promoted their learning about aquaponics, consistent with the ALQ records where 83–89 % of the players reported a similar experience (Fig. 6c). Likewise, 28 participants expressed motivation to implement an aquaponics system in their communities (between 74 and 83% of the game groups in the ALQ) (Fig. 6c); 27 praised the innovation of the productive system; and four recognized in the game, experiences such as cooperation, taking risks, and trial-and-error efforts to win the game. Likewise, 16 players mentioned that, at the beginning, the rules were confusing, but during the development of each game, they managed to understand the objectives. This is similar to what Boissau et al. (2004) registered.

On the other hand, comments were also received for the improvement of AQUAPONICS. Among these, a total of 68 people complained that the rules of the game were complicated or confusing; this coincides with the appreciation of 24–43 % of the ALQ records (Fig. 6c), with the highest values coming from the elders group. This can be related to the complaint of 31 people, mainly older adults, about the inconvenience of the game board with small-sized pieces, images, and letters. Additionally, 10 people, mainly in the young category, recommended digitalizing the game, continuing the trend of using technology-enhanced games over board games and role plays (Hallinger et al., 2020). However, this preference could exclude communities with less access to technological tools and specific age groups with less knowledge of the use of technology, such as older adults. In addition, the observations of eight participants who consider that contextualizing environmental hazards to their region will further strengthen the communication of specific learning achievements through stories or narratives are highlighted (Nebel et al., 2017) and will lead to immersing themselves into a game role, which could have impacts on their behavior and decision-making outside the game (Gordon and Yiannakoulias, 2020). Finally, 172 people stated that they found AQUAPONICS: "pleasant," "good," "interesting," "entertaining," or "fun," consistent with the responses obtained in the ALQ (Fig. 6c).

3.4. Identification of learning elements

In AQUAPONICS, two fundamental learning aspects were identified: i) the elements of the game of a playful nature and ii) the gamification mechanisms related to the basic needs of human beings, such as survival. These elements incorporate, in a precise manner, the visualization of an objective, immediate response, player adaptation, reward, and failure with a learning opportunity, which fit the requirements for a game to be interesting and useful for learning (Luo, 2022). Likewise, at the end of the game, participants demonstrated a willingness to learn about food production in aquaponic systems (Figs. 6 and 7), which is essential in a learning game (Manni et al., 2017).

Similarly, the game experience involved participants in decision-making processes and strategy formulation within the framework of addressing the specific challenge of feeding a community of 100 people, consistent with what Chen et al. (2014) reported. In addition, the game promotes in the participants a deeper level of commitment to their learning to the extent that it requires constant interaction with the teaching content (Kirriemuir and McFarlane, 2004). Therefore, in this study, it was possible to identify that AQUAPONICS promotes experiential learning and favors authentic learning oriented to problem-solving, the development of critical thinking, and the increase of collective efficacy, which encourages curiosity about aquaponics, as has been proposed by Cheng et al. (2019).

On the other hand, the adaptivity of participants is one of the game features that favors learning since it involves challenges, attraction, and fun (Pivec and Kearney, 2007), keeping the players motivated to overcome the different challenges that the game poses (Conati and Zhou, 2002). Thus, in this study, only 0.4 % of the participants dropped out of the game, and 99.6 % continued until completion. Overall, the results obtained from the ALQ indicate that AQUAPONICS provided an effective learning environment, as it incorporated some of the elements proposed by Kasvi (2000), including a) high interaction and feedback, b) it should be motivating, c) it provides a continuous sense of challenge, d) it provides a sense of commitment to the goal of feeding a community, and e) it provides adequate tools for each task. Likewise, learning is stimulated visually through the elements of the game board representing the aquaponics system and intuitive and reflective learning since participants must develop strategies and learn from their failures to win the game. This leads them to develop a general knowledge of aquaponics, consistent with the game-based learning approach (Murphy, 2016).

In general, every attempt a player made to overcome each challenge was an opportunity to put into practice the understanding gained of the logic involved in transitioning from a traditional farming system to an aquaponics production system. Thus, in each round, the player gains a conscious understanding of the general logic and main components of an aquaponics system that enables the player to make decisions within the game and allows him or her to achieve a goal. When players need more than one attempt to move from one round to another (from one challenge to another), learning is reinforced through trial and error (van der Meij et al., 2011). This allows for meaningful self-regulation to recognize the general logic and principles that define an aquaponics system and its main differences in relation to traditional farming (Koriat, 2008).

3.5. Main findings

From observations made throughout the study and the opinions of the players during the debriefing time with the players, AQUAPONICS was recognized to achieve a greater commitment from young people, who interacted more with the elements of the game and were more motivated to take action, solve problems, and unravel the challenges of each round, which is consistent with what was reported by Manzano-León et al. (2023). So, overall, the following lessons are highlighted in the players:

- They recognize the stages to start an aquaponics cultivation system.
- They identify the three basic components of aquaponics: i) plant cultivation, ii) fish cultivation, and iii) biofilter.
- They recognize that the biofilter is necessary to maintain the quality conditions in fish and plant cultivation.
- They recognize that the permanent presence of fish in the system supports the production of nutrients for the plants.
- They identify hydroponics as an adequate transition from traditional agriculture to aquaponics while the bacteria mature in the biofilter; later on, it is possible to integrate the aquaculture system, forming aquaponics production through a closed water cycle.
- They recognize that failures in the game are helpful as reference information to be successful at each stage of the game.
- Some participants indicated that the game offers them a general perspective of aquaponics; in many cases, they express their desire to learn more.
- After playing AQUAPONICS, the participants were observed to be more proactive, participative, and open to the know-how (knowledge) discussion, as Rodela et al. (2019) reported. It has also been highlighted that the participants were open to entrepreneurship in aquaponics in their own contexts, which coincides with the findings of Pivec and Kearney (2007). In general, cooperation was recognized as a promotor of knowledge transfer between participants and the exploration of new individual and group strategies, as Hossard et al. (2022) reported.

4. Limitations and scope

In this study, the ALQ was applied to collect information and perceptions from participants about the game. It consisted of questions with dichotomous answers (Yes/No options), which limits a broader correlation analysis to identify possible influences between the variables analyzed. Therefore, other researchers are encouraged to consider using ordinal qualitative variables, which define a degree of knowledge or perception in the participants. Correspondingly, although the willingness or ability to migrate to an alternative productive system such as aquaponics was not evaluated in this study, AQUAPONICS contributed to increasing the interest in local developing community inhabitants to consider entrepreneurship in aquaponics. According to the data obtained in the ALQ, it is necessary to adapt the rules of the game and its explanation to make it more accessible, especially to the elders. Additionally, questions about the ease with which color-blind people recognize elements of the game board were not included since none of the authors are experts in this area of knowledge. However, the game design involved criteria that can contribute to improving the gaming experience for this population. Finally, sufficient space must be guaranteed in the gaming sessions for knowledge sharing to occur before and after playing, as recommended by Hertzog et al. (2014).

Similar to the report of Gordon and Yiannakoulias (2020), this study presents a series of characteristics that limit its generalization, so it may be possible that the results obtained in the municipalities of Tolima could vary for other communities due to the demographic and cultural particularities of each region. On the other hand, there is a lack of external validation that confirms that the actions taken by the participants during the game represent their decisions in reality; therefore, the analysis is limited for the purposes mentioned in the study.

Finally, based on suggestions from the younger population participating in the study, a digital version of AQUAPONICS was developed and is available in the database of Osma et al. (2024), which includes boards, instructions, and video tutorials to play the game.

5. Conclusions

The dissemination of concepts that contribute to sustainable development to a broad general public promotes the involvement of sustainability in their daily decision-making. AQUAPONICS aimed to disseminate a sustainable production system incorporating alternative educational methods, such as a serious game, because implementing an aquaponic system can be complex without extensive technical training. Therefore, developing a serious game, such as AQUAPONICS, offers a general perspective on food production in aquaponics systems for community entrepreneurship. The results obtained indicate that the board game generated interest and engaged most participants regardless of their age, educational level, occupation, or previous knowledge of production systems, demonstrating the scope of the purpose of the game and its relationships with the promotion of sustainable practices in food production and social interaction for learning, as well as motivation to learn, especially in adults and young people.

In this sense, researchers are encouraged to develop game-related approaches that facilitate the performance of people with color blindness and contribute to promoting innovative productive systems framed in sustainability to capture the interest of communities and entrepreneurs. Likewise, games aimed at developing prototyping skills are desirable as a strategy for appropriating technologies in communities, which can generate opportunities to lead learning processes for young people.

Future studies could guide a more robust didactic sequence design that involves educational strategies for the strengthening and consolidation levels, with aquaponics being the strategy for the initiation level. This leads to the question of what educational explorations for non-formal and rural contexts could be considered for learning aquaponics from a collaborative family perspective.

CRediT authorship contribution statement

Luis E. Peña: Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Johann F. Osma:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Juan D. Márquez:** Writing – original draft, Methodology, Formal analysis, Data curation. **Mónica Álvarez-Bustos:** Writing – original draft, Methodology, Investigation, Conceptualization. **Lucia Fuentes-Forero:** Investigation, Conceptualization. **Felipe Sierra-Hurtado:** Investigation, Conceptualization.

Data availability

Data will be made available upon request from the corresponding author, and the database used in this study is available at https://doi.org/10.17632/rbtssbsv56.1.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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