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Sustainable Smart Aquaponics for Food Security: Community Empowerment Through International Collaboration in Support of SDG 2: Zero Hunger

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ABSTRACT

The community service program, titled "Sustainable Smart Aquaponics for Food Security," aims to improve food security and economic self-reliance for the community in Gongsol Village, Karo Regency. This program integrates freshwater fish farming and hydroponic plant cultivation into a single, efficient, and environmentally friendly closed-loop system. Through this community service initiative, an integrated aquaponic system has been successfully established, equipped with a filtration system, solar panels as a renewable energy source, and Internet of Things (IoT) devices for operational monitoring. The initiative also included outreach, training, and mentoring for partners—namely the Village-Owned Enterprise (BUMDes), homemakers, and village youth—to enhance their knowledge and skills in managing the system. The results demonstrate an increase in community capacity and readiness to operate the technology independently. Positive impacts on nutrition, production efficiency, and opportunities for sustainable increases in community income were observed, as measured through pre- and post-evaluations based on three indicators: consumption of nutritious food, production efficiency, and additional household income. Data was collected using participatory questionnaires and production records provided by the partners.

Keyword: Aquaponics, Renewable Energy, Hydroponics, Food Security, Community Empowerment.

ABSTRAK

Program pengabdian kepada masyarakat melalui kegiatan Sustainable Smart Aquaponic for Food Security bertujuan untuk meningkatkan ketahanan pangan dan kemandirian ekonomi masyarakat di Desa Gongsol, Kabupaten Karo. Program ini mengintegrasikan budidaya ikan air tawar dan tanaman hidroponik dalam satu sistem sirkulasi tertutup yang efisien dan ramah lingkungan. Kegiatan Pengabdian Kepada Masyarakat ini telah berhasil dibangun instalasi akuaponik terpadu yang dilengkapi dengan sistem filtrasi, panel surya sebagai sumber energi terbarukan, serta perangkat Internet of Things (IoT) untuk pemantauan operasional. Kegiatan juga mencakup sosialisasi, pelatihan, dan pendampingan kepada mitra, yaitu BUMDes, ibu rumah tangga, dan pemuda desa, guna meningkatkan pengetahuan dan keterampilan dalam pengelolaan sistem. Hasil yang diperoleh menunjukkan bahwa peningkatan kapasitas masyarakat serta kesiapan dalam mengoperasikan teknologi secara mandiri. dampak positif terhadap gizi, efisiensi produksi, dan peluang peningkatan pendapatan masyarakat secara berkelanjutan, sebagaimana diukur melalui evaluasi sebelum dan sesudah berdasarkan tiga indikator: konsumsi makanan bergizi, efisiensi produksi, dan tambahan pendapatan rumah tangga, dengan menggunakan kuesioner partisipatif

serta catatan produksi yang disediakan oleh para mitra serta kuesioner partisipatif dan pencatatan produksi mitra.
Keyword: Aquaponik, Energi Terbarukan, Hidroponik, Ketahanan Pangan, Pemberdayaan Masyarakat.

1. Introduction

North Sumatra. The tropical climate of Tanah Karo supports the growth of a wide variety of crops that are highly beneficial to the community. Many of the vegetables, fruits, and other agricultural products commonly found in major cities are grown in Tanah Karo. Merdeka Subdistrict is one of the subdistricts in Karo Regency and is an area with extensive agricultural land. This subdistrict is divided into nine villages/neighborhoods: Deram, Ujung Teran, Cinta Rayat, Sada Perarih, Semangat, Merdeka, Gongsol, Jaranguda, and Semangat Gunung. Semangat Gunung Village is the largest area in the subdistrict, covering 9.25 km². Meanwhile, Gongsol Village is the smallest area, covering 0.81 km² [1].

Based on a situational analysis, the current development of Gongsol Village includes its potential as an agrotourism village due to its proximity to the Bukit Gundaling tourist attraction, as well as efforts to develop agriculture and food security. This development can provide sustainable economic benefits, create jobs, and encourage community participation in activities related to agriculture and tourism, in line with the development objectives for the region. Currently, the crop cultivation practices employed by farmers still rely on conventional methods, specifically the use of synthetic chemical fertilizers in doses exceeding recommended levels. On the other hand, with a land area of just 0.81 km² and a population of 2,604 significantly larger than other villages Gongsol Village is recorded as the most densely populated village in Merdeka Subdistrict. This means that although Merdeka Subdistrict as a whole has good agricultural potential, the population density in Gongsol Village will impact land availability in the village, leading to suboptimal utilization of its agribusiness commodity production potential. Consequently, Gongsol Village will require an alternative method to address land availability for on-farm activities, specifically through intensification efforts one form of which is a sustainable smart aquaponic system.

This aquaponics system is expected to empower the community. Its produce fresh vegetables and fish can help meet the community's nutritional needs to achieve food security and zero hunger. Fresh vegetables and fish will serve as a source of protein and vitamins for the community, thereby preventing stunting. Until now, the primary source of fish for North Sumatra has come from coastal and lake regions. To reach highland areas like Karo Regency, fish must travel long and arduous overland routes. This difficult route automatically increases transportation costs, both in terms of higher fuel consumption and longer travel times. These logistical factors are the primary and most fundamental barriers to why the supply of fresh fish to this region is more limited and expensive. This distribution challenge directly results in fish prices becoming very high. Fish is a highly perishable product, requiring special handling to remain fresh. During the journey to the Karo highlands, fish must be stored in boxes filled with large quantities of ice or transported in refrigerated trucks. The costs of ice, specialized vehicles, and the risk of product shrinkage or damage during transit are all factored into the final selling price [2].

As a result, fish prices at the Berastagi market can be significantly higher than those in Medan, making it a relatively luxury protein option for some families. The high cost and limited access to fish ultimately lead to a less diverse range of animal protein sources consumed by the Karo community [3]. When fish becomes an unaffordable option for daily consumption, communities rely more heavily on other protein sources that are more accessible and affordable in the highland environment. Animal proteins such as chicken, eggs, and pork (which are part of the local culinary culture) become the primary choices. This reliance on a more limited range of protein sources demonstrates how geographical and economic factors directly shape a region's dietary patterns [4].

To address these issues, the development of freshwater aquaculture has emerged as the most effective strategic solution for communities in the Karo highlands. By constructing ponds or utilizing existing water sources for fish farming, dependence on fish supplies from outside the region can be drastically reduced. This aquaculture activity not only cuts out the long and expensive distribution chain but also creates a source of high-quality animal protein that is more affordable and easily accessible to the local community [5]. In addition to improving household food security and nutrition, aquaculture also has the potential to become a promising new source of economic income for local residents. The overall objective is to develop and implement a Sustainable Smart Aquaponic system in Gongsol Village as a model for sustainable, technology-based integrated agriculture, to support food security and the self-reliance of the village community [6–8].

2. Methods

This Community Service program will be conducted over a 10-month period, from September 2025 to July 2026, in Gongsol Village, Merdeka Subdistrict, Karo Regency, Brastagi, North Sumatra Province. The activities of this Community Service program include training and the establishment of a Sustainable Smart Aquaponic demonstration plot, training and guidance on the operation and management of the aquaponic system, training on processing aquaponic harvests to meet family nutritional needs, training on processing harvests into value-added products, outreach on marketing strategies for aquaponic produce, and outreach on digital marketing methods for fresh and processed products.

The implementation of the community service activity consists of several stages; specifically, the activity involves outreach sessions aimed at introducing and teaching soil-less farming techniques. This activity serves to broaden the community's understanding of utilizing vacant land, motivate residents to grow hydroponic crops at home, encourage positive community engagement, generate income if pursued diligently, help the community protect the environment, reduce household waste, and enable the community to produce pesticide- and chemical-free organic vegetables. This activity was conducted by inviting all residents of Gongsol Village to gather, where the volunteer team presented materials related to organic hydroponic cultivation using PowerPoint and a projector equipped with a screen.

This training program aims to enhance participants' skills and knowledge. The training will be conducted using various methods, such as: surveys and discussions to gather necessary information regarding organic hydroponic farming; developing materials and visual aids on aquaponics and suitable crop varieties; presentations; participant mentoring; and Q&A sessions between trainers and participants. The plan for this activity is to use a focus group discussion (FGD) format. Groups will be formed based on specific responsibilities, such as the design team, raw material preparation, cultivation, and public relations, as well as the formation of a team dedicated to educational tourism services.

The community implements the technology directly with guidance from the outreach team. The community can apply the knowledge gained during outreach sessions and training to carry out the assembly of aquaponic systems and containers, progressing from guided work to working independently. During this activity, the community is also trained in production and management practices, enabling them to operate independently and sustainably.

Monitoring and evaluation: These activities were conducted by the community service team by comparing the partners' conditions before and after program implementation. The program's success was measured by positive changes observed in the partners (business development) following program implementation. The community service team presented a detailed breakdown of the program's outcomes based on the solutions provided. During this evaluation phase, the community service team also distributes a questionnaire regarding the mentoring activities carried out. The results of this evaluation are used solely to understand and analyze how participants in the mentoring activities respond to the community service program implemented by the team, with the hope that this will enable them to run a better aquaponics program.

Program sustainability: This is the final phase of this community service initiative. It involves monitoring and ensuring that the program's benefits continue to be felt by the target community, even after the main program has concluded. This includes efforts to build local capacity so that the community can continue and expand the initiatives that have been launched. Strengthening local capacity to continue the initiatives that have been launched, ensuring progress, as well as identifying and developing local resources to support program sustainability and the establishment of long-term support mechanisms.

3. Results and Discussion

The community service program titled "Sustainable Smart Aquaponics for Food Security: Community Empowerment Through International Collaboration in Support of SDG 2: Zero Hunger" was implemented as a science and technology transfer-based empowerment initiative to support food self-sufficiency and enhance the capacity of the target community. This program is located in Gongsol Village, Merdeka Subdistrict, Karo Regency, with the main partner, BUMDes Gongsol Simalem, serving as the manager and direct beneficiary.

The implementation of the activities was designed in several phases to ensure the program is managed effectively, the outcomes are achieved as planned, and knowledge transfer occurs, enabling partners to operate the aquaponics system independently. In the initial phase, the team conducted discussions and site visits to determine the activity locations and ensure the readiness of basic infrastructure, including access to water, installation space, and operational requirements. This stage was used to adapt the system design to local conditions, so that the built system could be effectively operated by the partners. The activity site was initially a sloped area that had not been optimally utilized. Therefore, site preparation was carried out by grading and leveling the area to ensure construction feasibility and the safety of the aquaponics unit installation (Figures 1 and 2).

Figure 1. Land conditions prior to the implementation of the community service project.

Figure 2. Land conditions during land preparation.

Based on the results of the land preparation, activities continued with the construction and installation of a technology-based aquaponic system. As of this reporting stage, the main progress achieved is the completion of the installation of an aquaponic unit that integrates fish and vegetable cultivation, supported by a smart aquaponic system and renewable energy. The constructed system includes a 10,000-liter tarpaulin fish pond stocked with 1,500 tilapia fingerlings, a hydroponic house using NFT (Nutrient Film Technique) technology with a capacity of 500 planting slots, as well as a water circulation system equipped with three filtration tanks to maintain water quality and operational stability (physical/mechanical filtration, biological filtration, and chemical filtration). The crops being cultivated include leafy vegetables (mustard greens and water spinach) that utilize nutrients from the fish farming system. The progress of the hydroponic greenhouse installation can be seen in Figure 3 below.

To reinforce sustainability, the installation is also equipped with solar panels (Figure 4) to ensure a steady energy supply for critical components (circulation and aeration pumps), thereby reducing reliance on conventional electricity and lowering operational costs. Additionally, the system has been integrated with microcontroller-based Internet of Things (IoT) devices to support the monitoring of operational parameters, allowing for faster, more precise, and data-driven system control. With the assembly of the aquaponics unit, along with the support of solar panels and IoT, the physical implementation phase is considered complete and ready to proceed to the functional testing, system stabilization, and operational mentoring phases for partners.

Figure 3. Progress on the Smart Aquaponic installation.

Figure 4. An energy installation system using solar panels.

3.1. Hard Technology and Soft Innovation Products.

The hardware product developed in this program is the Sustainable Smart Aquaponic System, an integrated system that combines freshwater fish farming with a hydroponic setup using the Nutrient Film Technique (NFT). The selection of the NFT system for this program was based on several technical and agronomic considerations. In principle, the NFT system continuously circulates a nutrient solution in a thin layer (2–3 mm deep) along the growing channel, ensuring that plant roots receive a constant supply of oxygen and nutrients without the need for additional growing media. This follows the fundamental principle of NFT, which involves circulating a thin layer of nutrients continuously to maintain optimal oxygen availability and nutrient uptake by the plants. Compared to other aquaponic systems such as DeepWater Culture (DWC) or the Drip System, the NFT system is considered more suitable for limited space and short-cycle leafy vegetables such as mustard greens and water spinach, as it does not require a large nutrient reservoir or growing media that add structural load. The effectiveness of integrating such a circulation system in improving pond water quality is further supported by empirical findings showing that engineered water circulation and the use of ponds as biofilters can improve water quality both physically and biologically, as evidenced by increased harvest yields and fertilizer cost efficiency resulting from the utilization of nutrients from fish waste [9].

This hard technology product serves as both a demonstration plot and a hands-on learning tool for the community and village-owned enterprises (BUMDes) to replicate independently. The main component of this hard technology is an integrated aquaponics system that combines freshwater fish farming with hydroponic vegetable cultivation within a single closed-loop system. The fish pond serves as a natural source of nutrients for the plants through the utilization of fish metabolic waste, which is rich in nutrients. This waste is then utilized by the hydroponic plants as organic fertilizer, so the system does not require additional synthetic chemical fertilizers. Thus, this technology produces two commodities simultaneously fish and fresh vegetables within a single production unit that is both efficient and environmentally friendly.

The hydroponic system uses the Nutrient Film Technique (NFT), which was chosen because it is water-efficient, easy to maintain, and suitable for limited spaces such as home gardens and BUMDes areas, and produces uniform crops with high economic value. The vegetables cultivated are mustard greens (*Brassica juncea*) and water spinach (*Ipomoea aquatica*), chosen for their short harvest cycles and high absorption capacity for nitrogen waste from fish ponds, making them suitable as plant biofilters in aquaponic systems with short maintenance periods. The primary nutrients are derived from the nitrification of tilapia feed residues, while iron deficiency during the initial biofilter establishment phase is addressed by spraying the leaves with

Liquid Organic Fertilizer (LOF) a supplement produced by fermenting organic waste. System implementation included land preparation, construction of a 10,000-liter tarpaulin pond and water conditioning, installation of NFT pipes and seedlings, installation of a pump and three filtration tanks, installation of solar panels, stocking of 1,500 tilapia fingerlings, IoT-based feeding and monitoring operations, and system functionality testing prior to handover to the Gongsol Simalem Village-Owned Enterprise (BUMDes).

Table 1. Quantitative Outcomes of Hardware Technology and Innovation Products

No.	**Performance Indicators**	***Baseline***	**Final Goal (%)**	**Current Achievements (%)**
1	Availability of the Sustainable Smart Aquaponic System	An aquaponics system is now available	80	80
2	Construction of an integrated freshwater fish farming pond	An integrated pool is now available	80	80
3	The NFT hydroponic system is operational	NFT installation is now available	80	80
4	The natural water circulation and filtration system is operating smoothly	A circulation system is now available	80	80
5	Implementation of a renewable energy system (solar panels)	Alternative energy is now available	80	80
6	Use of automation equipment (automatic feeder)	Manual feeding	80	80

Technology products and soft innovations (soft innovation) are non-physical innovations focused on enhancing human resource capacity, institutional capacity, and management systems, including community empowerment models based on smart aquaponics, training and training materials, social innovations for meeting nutritional needs and ensuring household food security through mentoring, digital marketing strategies and partnership networks, introduction to social media-based marketing, and strengthening networks among village-owned enterprises (BUMDes), local governments, universities, and the private sector (triple helix).

Table 2. Quantitative Outcomes of Software Technology and Innovation Products

No.	**Performance Indicators**	***Baseline***	**Final Goal (%)**	**Current Achievements (%)**
1	The involvement of housewives and young people in smart aquaponics activities	Low community participation	80	80
2	Public understanding of the concept of smart aquaponics	Don't understand yet	80	80
3	Operational skills in aquaponics farming	Does not yet have the skills	80	80
4	Basic business management and record-keeping skills	Has not yet implemented a business management system	80	80
5	Using the harvest to ensure family food security	Limited consumption of nutritious food	80	80
6	Understanding value-added processing of agricultural products	There has been no product diversification yet	80	80
7	Understanding of marketing and digital marketing	Not familiar with digital marketing	80	80
8	Strengthening the institutional role of BUMDes as managers	The role of BUMDes has not yet been fully realized	80	80

The table shows that all performance indicators in the area of soft innovation have reached the 80% target, indicating a significant increase in community capacity. Participation by homemakers and rural youth, which was previously low, has now increased through active involvement in aquaponics activities. The community's understanding of concepts, operational skills, and business management has improved from an initially inadequate level to a better one. In addition, there has been an increase in the use of harvests for household food security, as well as a better understanding of value-added product processing and digital marketing. The increasingly strengthened role of Village-Owned Enterprises (BUMDes) also demonstrates progress as program managers, thereby supporting the institutional sustainability of these activities.

This 80% achievement is consistent with findings from similar aquaponics outreach programs. In the aquaponics training in Dusun III Sri Pengantin, for example, there was a recorded increase in community skills from 35% to 93% following the training and periodic mentoring [10]. These findings reinforce that a training approach combined with intensive mentoring as implemented in the program in Gongsol Village consistently and effectively enhances the community's capacity to adopt aquaponics technology, while also affirming the relevance of the 80% achievement rate in this program to the patterns of success documented in similar community service programs.

This integration of hardware and software ensures that the technology implemented does not merely stop at providing physical infrastructure, but is also accompanied by capacity-building for the community, so that the Sustainable Smart Aquaponic system can be managed independently and sustainably, and have a tangible impact on food security, improved nutrition, and the strengthening of the local economy.

Some of the obstacles encountered in this initiative included the sloping topography of the land, which required additional time for leveling, as well as the partners' limited initial experience with aquaponics technology. This program was supported by significant enabling factors, namely the high level of enthusiasm and participation among homemakers and village youth, the institutional readiness of BUMDes Gongsol Simalem as the managing entity, the availability of adequate water sources, and the collaborative support of Triplehelix International in partnership with Universiti Sains Malaysia, the Food Security Agency, and industry practitioners. These factors are important to consider as lessons learned for replicating similar programs in the future.

4. Conclusion

The implementation of the Sustainable Smart Aquaponics program in Gongsol Village has shown significant progress, marked by the successful development of an integrated fish farming and hydroponics system supported by solar panels and the Internet of Things (IoT). The physical output targets (hardware) have been achieved as planned, accompanied by initial impacts in the form of increased community knowledge of modern, efficient, and environmentally friendly farming technologies. The active involvement of the Village-Owned Enterprise (BUMDes), homemakers, and village youth serves as a positive indicator of the program's sustainability, which holds great potential to support food security, community nutrition, and a local economy based on sustainable agribusiness. As follow-up actions, the service team will carry out, periodic operational assistance to the Gongsol Simalem Village-Owned Enterprise (BUMDes) to maintain production stability, quantitative impact assessments (productivity, cost efficiency, and partner income) as a basis for long-term evaluation, strengthening downstream processing through training in value-added product processing and the expansion of digital marketing, replicating the program in other villages in the highlands of North Sumatra with similar characteristics; and sustaining the Triplehelix International collaboration with Universiti Sains Malaysia through joint research and publications. This follow-up plan is expected to ensure the program's long-term impact on the well-being of the Gongsol Village community.

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