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Decentralized Wetland-Aquaponics Addressing Environmental Degradation and Food Security Challenges in Disadvantaged Rural Areas: A Nature-Based Solution Driven by Mediterranean Living Labs

Fatima Yahya [1], Antoine El Samrani [2], Mohamad Khalil [1], Alaa El-Din Abdin [3], Rasha El-Kholy [3], Mohamed Embaby [3], Mohab Negm [3], Dirk De Ketelaere [4], Anna Spiteri [4], Eleanna Pana [5] and Vasileios Takavakoglou [5,*]

[1] Azm Research Center, EDST, Lebanese University, Tripoli P.O. Box 100, Lebanon; fatimayahya91@hotmail.com (F.Y.); mohamad.khalil@ul.edu.lb (M.K.)
[2] Laboratory of Geoscience, Georesources and Environment-L2GE, Faculty of Science, Lebanese University, Campus Fanar EDST, Beirut P.O. Box 90656, Lebanon; antoineelsamrani@ul.edu.lb
[3] National Water Research Center, Egyptian Chinese University, Cairo 19346, Egypt; alaa_ea_abdin@yahoo.com (A.E.-D.A.); rasha.elkholy@nwrc.gov.eg (R.E.-K.); mohamed_embaby@nwrc.gov.eg (M.E.); mohabnegm@hotmail.com (M.N.)
[4] Integrated Resources Management Company, Ltd., 24 Pope Benedict XV Square, 1083 Senglea, Malta; dirk@environmentalmalta.com (D.D.K.); anna@environmentalmalta.com (A.S.)
[5] Hellenic Agricultural Organization "DIMITRA", Soil and Water Resources Institute, 57001 Thessaloniki, Greece; eleannapana@gmail.com
* Correspondence: v.takavakoglou@swri.gr; Tel.: +30-2310-473-429

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Abstract: The Mediterranean region is highly vulnerable to climate change, soil and water resource degradation, and biodiversity loss. These challenges disproportionately affect disadvantaged rural areas, impacting both natural resources and the livelihoods of local agricultural societies. Urgent transformative measures are essential to address land and water management as well as food security challenges in these disadvantaged areas. Living labs are being called upon to play a key role in addressing these challenges through the development of Nature-based Solutions (NbSs) that are able to provide environmental and socioeconomic benefits towards the achievement of Sustainable Development Goals. The aim of this work is to provide insights on an open innovation ecosystem of Mediterranean Living Labs for the synergetic development and participatory assessment of decentralized wetland-aquaponics, as NbSs are able to address environmental and food security challenges in disadvantaged rural areas. The study addresses the knowledge gap of Living Labs contribution to the development of decentralized wetland-aquaponics and the limited research on small-scale aquaponics systems in rural Mediterranean settings, while revealing the role of public participation in ascertaining the solution and evaluating its feasibility and impacts in light of the local social values and interests in the mountainous area of Akkar al-Atika in Lebanon.

Keywords: living-labs; cross-border cooperation; participatory; aquaponics; constructed floating wetlands; food security; environmental management; impact assessment; Nature-based Solutions; pollution control; water resources; climate change; Mediterranean

1. Introduction

The Mediterranean is one of the most vulnerable regions in the world to the impacts of climate change, water scarcity, land degradation and biodiversity loss [1]. These threats are especially severe for Mediterranean Areas that face Natural or other specific Constraints (ANCs), such as mountainous areas, islands and low-income areas with clear biophysical limitations. In these areas, climate change affects not only natural resources but also local societies and economies that depend on agricultural production. As indicated by recent remote sensing studies, the combined impacts of both climate and human interventions in Land Use and/or Land Cover changes may not only harm water-dependent natural ecosystems such as lakes and wetlands [2], but also artificial ecosystems related to agricultural production (e.g., paddy fields) [3], and thus restrict the access of rural communities to fundamental ecosystem services for their survivability [4]. In such disadvantaged areas, land degradation, along with unsustainable exploitation of water resources and water scarcity, lead to increased use of agrochemicals and high production costs, food insecurity, economic decline and eventually depopulation. Therefore, there is an evident need for transformative measures of land and water management to sustaining the livelihoods of local societies [1,5].

The implementation of Nature-based Solutions (NbSs) in the food production process can contribute to sustainable environmental management while also providing multiple socioeconomic benefits [6]. In particular, solutions that rely on ecosystem services could be integrated with modern food production processes through an ecological approach with a dual objective of pollution control and safe food production. In this perspective, decentralized, low-cost aquaponic systems that take advantage of wetland ecosystem functions and services could be considered an effective solution for food production based on circular economy concepts that minimize inputs and waste. In the last decade, food production systems such as closed-loop aquaponics systems based on floating wetlands principles for primary production and/or using constructed wetlands as biofilters [7] have attracted considerable attention from academics and practitioners [8,9]. These systems are part of the circular bioeconomy, which is an emerging field of research [10], but their global adoption is described as "small and limited" [11,12], while the assessment of their positive environmental and socio-economic impact is still limited [13].

The adaptation of such NbSs to the needs of local societies, especially in disadvantaged areas, is of prominent importance for the Mediterranean. In this process, the Living Labs approach can be part of an institutional transformative change that combines top-down and bottom-up strategies for achieving sustainability [14]. Living Labs provide a collaborative environment that enables the integration of research and innovation processes in real-life communities and environments [15]. According to the United Nations General Assembly held in 2015, Living labs are seen as assets to achieve the Sustainable Development Goals (SDGs) and mainstream NbSs. A key factor in Living Labs' success is the engagement and active participation of stakeholders in both the development and assessment of NbSs, as these are two critical steps for their endorsement and adoption by local societies. However, recent studies indicate that the way in which Living Labs contribute to the development of operational solutions and sustainability transitions has yet to be explored in more detail [16,17]. Furthermore, there is a research gap in the participatory assessment of the feasibility and impact of NbSs [18] and especially of aquaponics as a Nature-based Solution in the Mediterranean context. Thus, there is an evident need for evaluations of decentralized small-scale systems tailored for disadvantaged rural areas and the opening of research outcomes and potential up to participatory approaches in real-world contexts [19].

The aim of this work is to provide insights on an open innovation ecosystem of Mediterranean Living Labs for the synergetic and participatory development and assessment of decentralized aquaponic systems that integrate floating wetlands services as NbSs for disadvantaged rural areas. The specific objectives of this work are: (a) to illustrate the critical role of Living Labs and the added value of cross-border cooperation and synergies in the development of decentralized wetland-aquaponics as operational agri-environmental NbSs for disadvantaged areas; and (b) to assess the feasibility of adoption and the potential environmental and socioeconomic impacts of decentralized systems using a bottom-up approach in the mountainous and low-income area of Akkar al-Atika in Lebanon.

2. Methodological Framework

2.1. Living Labs Deployment and Operation

This work has been realized within the framework of the Mara-Mediterra project, a research and innovation action funded by the PRIMA foundation under the EU Horizon 2020 Programme. The project demonstrates an open innovation ecosystem of six Living Labs in hotspots of land and water degradation around the Mediterranean, which include the Djelfa area in Algeria, the coastal area of the Nile Delta in Egypt, the North Aegean islands in Greece, the Akkar al-Atika mountainous area in Lebanon, the Lake Marmara area in Turkey, and a peri-urban area in Malta, which provides the pathways for the Living Labs operation.

In a local context, the Living Labs of Mara-Mediterra operate as user-centered innovation platforms based on a systematic approach to co-creating users and integrating R&D and innovation processes in real-life communities [20,21]. A multidisciplinary group of farmers, local community representatives and key stakeholders form a roundtable that guides the operations of the local living lab. These operations include experimental trials and demonstration actions for the co-deployment and co-assessment of eco-engineering and agro-ecological NbSs in real-life settings. At the international cooperation level, the Mara-Mediterra project provides a cross-border facilitation network that allows for the cross-fertilization of local knowledge. This is achieved through scheduled, dedicated events of knowledge and experience exchange between the coordinators of the Living Labs, the deployment of open-access audiovisual materials, and knowledge exchange missions in mirror hotspot areas. The above activities, at the local and cross-border level, create a favorable environment for participatory knowledge development and transfer that allow not only the deployment and validation of NbSs but also the customization and scaling out of best practices, as in the case of wetland-aquaponics, in order to integrate societal challenges and nature conservation across different scales and landscapes.

2.2. Bottom-Up Feasibility and Impact Assessment

The participatory feasibility assessment of wetland-aquaponics took place in the municipality of Akkar al-Atika in Lebanon. The population of this mountainous area is approximately 14,000, with a considerably low density (168 hab/km^2). The local economy is mainly based on forestry and agriculture. However, between 2001 and 2019, Akkar al-Atika showed a significant decrease in forest productivity due to forest fires and climate change impacts. Furthermore, the agricultural areas are impacted by the limited availability of water, while the groundwater is extensively overexploited due to uncontrolled drilling activities, resulting in the degradation of water resources and a decreasing level of the water table. To address these challenges, there is a need for transformative changes in the primary sector. Akkar al-Atika, as the case study area of the present work, is a representative disadvantaged rural area in Lebanon in which the introduction of decentralized wetland-aquaponics as NbSs through the local Living Lab could be a promising alternative to primary production.

To assess the feasibility and the potential environmental and socioeconomic benefits of wetland-aquaponics in Akkar al-Atika, a participatory bottom-up approach was applied through the Living Lab as a novel way to assess decentralized aquaponics systems, in contrast to common expert-driven assessments. In line with similar studies [22], structured interviews of the local stakeholders with the use of questionnaires have been used to assess the acceptance and potential benefits of decentralized wetland-aquaponics in the targeted area. The questionnaires consisted of 4 parts addressing social, technical, economic, and environmental factors related to the wetland-aquaponics system, and basic statistical tools were used for the exploratory analysis of the data.

In terms of data collection and characterization, the survey took place in the Municipality of Akkar Al-Atika, during the period June–September 2023 and consisted of 100 participants. Amongst the interviewed persons, 95% live in Akkar Al-Atika village all year and 5% live in the area only during the summer. The gender balance was 48% male and 52% female, while most of the participants had a secondary and higher education degree. The majority of the respondents had an average annual income of less than 600 USD (48%), and only 5% had an average annual income of over 2000 USD.

3. Synergies of Mediterranean Living Labs for Agri-Environmental Nature-Based Solutions: The Case of Wetland-Aquaponics

NbSs have the potential to offer long-term transformative pathways towards the sustainability of rural Mediterranean landscapes. Using the Living Labs approach, the overall ambition of Mara-Mediterra is to open up the NbSs innovation process to all active players so that new ideas can circulate more freely and eventually be transformed into tools, services and practices that address key environmental challenges in rural Mediterranean areas and foster a stronger culture of environmental stewardship and green entrepreneurship, thereby safeguarding sustainable rural landscapes and boosting the rural economy. In this effort, the synergistic effect and the added value of Living Labs cooperation across borders, within the open innovation ecosystem of Mara-Mediterra are illustrated in the development and evolution of the decentralized wetland-aquaponics concept as a NbS for areas that are facing natural or other specific constraints (Figure 1).

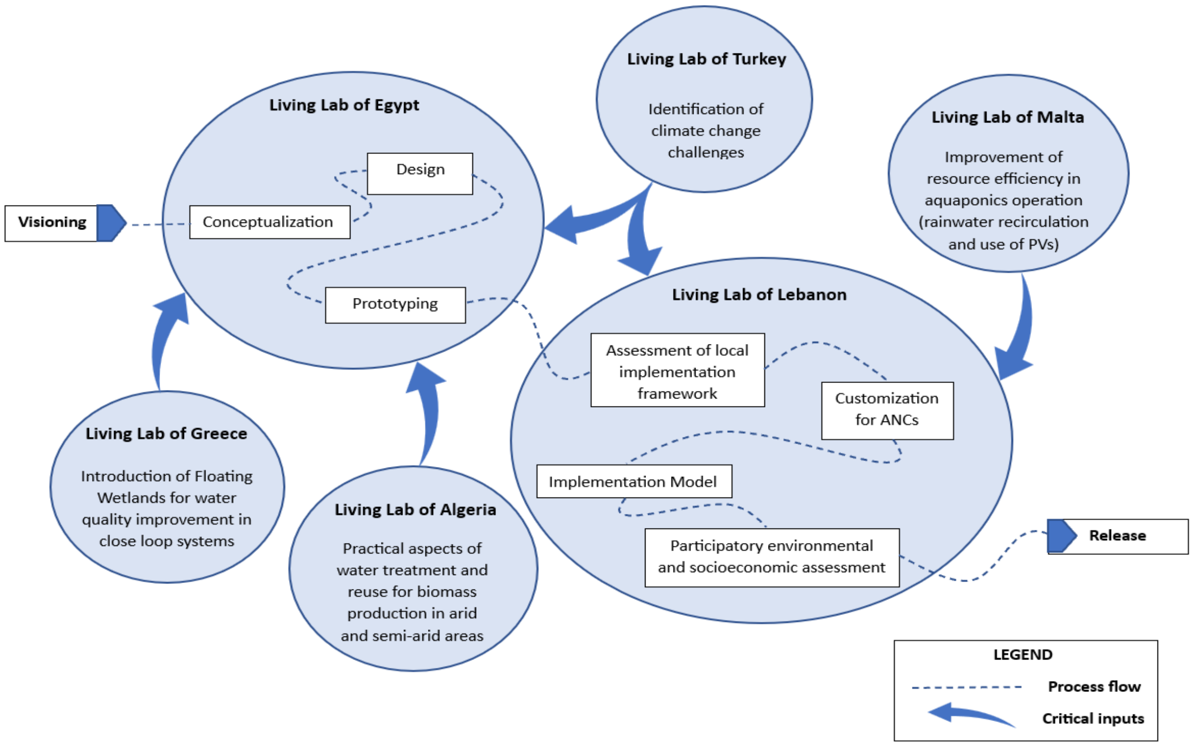

Figure 1. Cross border synergies of Living Labs within the open innovation ecosystem of the PRIMA funded Mara-Mediterra project. Visual representation of Living Labs contribution in the development process of decentralized wetland-aquaponics for Areas facing Natural or other specific Constraints (ANCs).

Aquaponics, which combines fish and plant production in a controlled environment, has been visioned by the participants in the Egyptian Living Lab as a possible solution for food production in the seawater intrusion-affected area of the upper Nile Delta, where biophysical limitations due to the degradation of soil and water quality have deteriorated agricultural production. The conceptualization and novelty of the design were achieved with the collaboration and critical contributions of three other Living Labs. Their key inputs included: (a) the introduction of floating wetlands simulating the provisional and regulatory wetland ecosystems' services for growing plants on floating rafts and for algae-based water quality improvement in a closed loop system; (b) the identification of climate change challenges for the operation of the system; and (c) the practical aspects of water treatment and reuse for biomass production in arid and semi-arid areas, from the Living Labs of Greece, Turkey and Algeria, respectively. Following a genuine participatory approach, the design of the wetland-aquaponics system was finalized in cooperation with the actors involved in the Egyptian Living Lab and the prototype unit was established by the Egyptian Chinese University, which coordinates the Living Lab in Egypt.

The prototype system triggered the interest of the Lebanese Living Lab for sustainable food production in the disadvantaged (mountainous and low-income) area of Akkar al-Atika, while the open ecosystem of the Living Labs network facilitated the cross-fertilization of knowledge and results across borders. Through the assessment of the local implementation particularities and priorities in the Lebanese Living Lab, an alternative system configuration and implementation model was formulated. Small, decentralized units were defined as more appropriate for the area in order to be used at the household/neighborhood level, while the system configuration was optimized to reduce construction and operation costs. The added value from other Living Labs was delivered in the form of scientific expertise for the assessment of water resource availability (Living Lab of Turkey) and in the form of ideas for the improvement of resource efficiency in the operation of the system, through the recycling of rainwater and the use of Photovoltaics (PVs) for energy autonomy (Living Lab of Malta).

The resulting design of the small-scale decentralized aquaponic system for Lebanon is aimed at increasing the farm productivity and profitability without significant water consumption, supporting poor families in producing their own fresh foods, and keeping farmers active during winter seasons, especially during periods of limited access to their lands. The proposed decentralized solution was finalized with the active involvement of stakeholders in the Living Lab of Lebanon, including both the co-design and the co-assessment of impacts on the local society (presented in Chapter 4).

The final system design (Figure 2) includes a 63 m^2 greenhouse (L × W × H/ 9 × 7 × 4.5 m) made from polyethylene films, which has the lowest cost in the market, a small-scale hydroponic system (16 pipes × 24 growing crop positions/pipe) and a small-scale aquaponic system (16 pipes × 24 growing crop positions/pipe). In each set-up, 4 inches of growing pipes, 2 inches of recuperation pipes, and net cups for growing crops of upper and lower diameter, respectively, 7.5 and 4.5 cm, are used. The distance between two horizontal positions is 22.5 cm and the distance between two vertical positions is 37 cm.

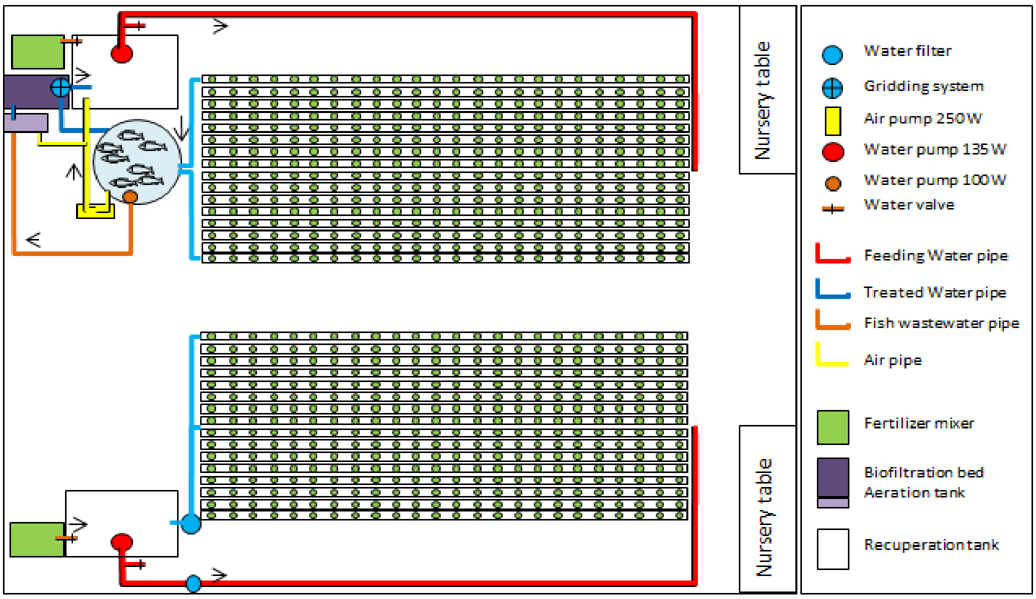

Figure 2. Conceptual design of aquaponic system layout.

The hydroponic growing pipes have a triangular prism shape and are connected to a main feeder tank of 1000 L by a 135 W circulating pump. The water is recirculated to the tank by gravity. A 50-L fertilizer mixing tank is connected to the feeder tank. The aquaponic, having the same prismatic shape, is directly connected to a 1000-L tank receiving treated water coming from the fish-rearing tank reservoir of 1000-L; the two tanks are aerated continuously. For the treatment of aquaculture effluents, a wetland biofilter is introduced in the design for pollution control since several studies have demonstrated that constructed wetlands can efficiently remove the major pollutants from catfish, shrimp and milkfish pond effluents under low hydraulic loading rates (between 0.018 and 0.135 m) and long hydraulic retention times (1–12.8 days) [23–25]. As physical and biochemical processes take place, the wetland functions as a natural filter for water quality improvement [26]. Effluents coming from the fish tank are treated inside an aeration tank connected to the biofiltration bed; the treated water outlet is connected to a gridding setup before being conducted to the feeder tank and to the fish rearing tank. A fertilizer mixing tank is connected to the feeder tank manually, and if needed. The whole system is operated by using three submersible pumps, two of which are 135 W and one of which is 100 W. Normally, the temperature in Akkar al-Atika fluctuates between 8 and 30 °C; thus, the temperature must be controlled. For this reason, the feeding tank is laid underground to minimize temperature fluctuation, while the power setup can support the operation of the system on or off-grid through photovoltaic panels if necessary to feed the heating water system when needed during extreme cold days. In addition to the economic aspects, stand-alone photovoltaics present additional climate-beneficial effects on reducing greenhouse gas emissions that should also be positively evaluated [27].

In addition, a nursery has been included in the design for a two-fold purpose: (a) to feed the hydro and aquaponic systems, and (b) to distribute the small plants to the farmers for free. This last objective is designed to attract farmers to attend the Living Lab, interact with the system, observe its functioning, and compare the growth in these two systems with their own traditional production. This strategy allows for corrective actions to be taken in the Living Lab, free access for continuous training, integration of farmers in decision-making and corrective procedures, and finally encouraging the farmers to reach the appropriate conclusions within their own particular context. Throughout this process, the farmers are comforted by the knowledge that they will be served by the know-how to find the right balance in the application of these practices.

Overall, it is highlighted that although the Living Labs in each country operate as intermediaries between local stakeholders, research organizations, key actors and decision makers [15], the establishment of a transnational network provides a cooperation platform for cross-border transfer of knowledge and experience for joint value co-creation, prototyping, or validation to expand innovation [28] and thus reveal and promote solutions across borders in order to address common problems. This approach, as adopted in the Mara-Mediterra project and supported by the PRIMA Foundation, creates the opportunity to re-establish meaningful connections between societies and ecosystems across borders. Thus, with the support of EU it demonstrates the strengthening of cooperation and relationships between Southern-Southern Mediterranean Partner States through direct interaction, while promoting their collaboration with Northern Mediterranean countries and actors towards sustainability. In this perspective, it allows for socio-ecological interventions that can provide, across borders, viable solutions [21] for areas that are facing natural or other specific constraints and common challenges, and thus promote the safeguarding of the environment and the livelihood of Mediterranean rural communities.

4. Participatory Assessment of Feasibility and Potential Impacts

4.1. Public Perception and Feasibility

The participatory feasibility assessment focused on appraising public perception, attitude, and social acceptance level of the decentralized wetland-aquaponics as NbSs in Akkar al-Atika. Based on the outcomes of the survey in Akkar al-Atika, a considerable part of local society (83% of the local stakeholders) considered decentralized wetland-aquaponics as an interesting economic activity for their area (Figure 3). This result indicates that the social acceptance of such systems is very high and paves the way for their potential future adoption in the area. This perception is in line with the FAO statement, according to which aquaponics finds its niche within the realm of sustainable yet intensive agriculture, particularly in applications tailored for family-scale operations [29].

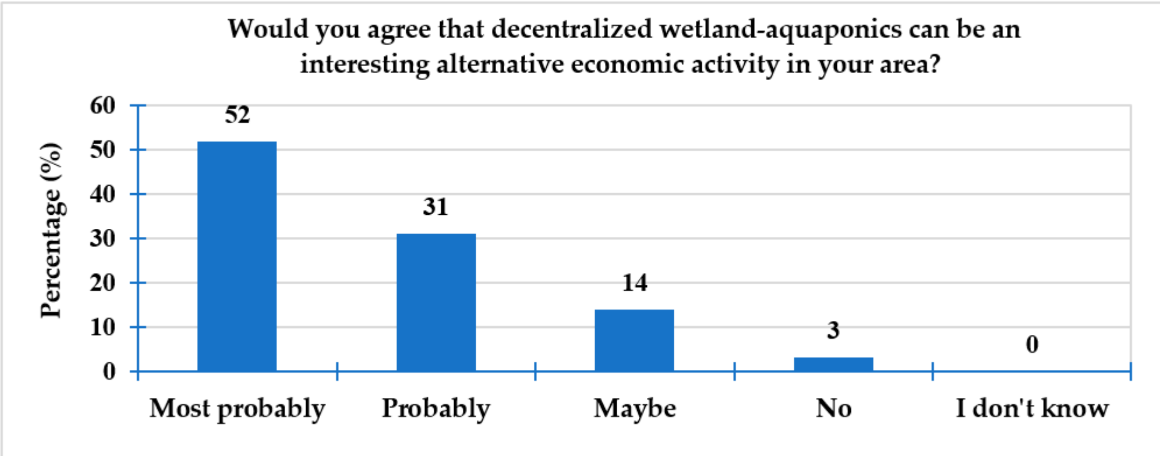

Figure 3. Public interest for decentralized wetland-aquaponics as an alternative economic activity in Akkar al-Atika.

The main reasons behind the acceptance and interest in decentralized wetland-aquaponics are the vision of a system that offers supportive and collaborative methods of vegetable and fish production and thus the opportunity to grow food in locations and situations where soil-based agriculture has been proven to be very challenging. The main reason for interest in the Akkar al-Atika area is related to food security for the local families, that is, the increase in food availability and quality for self-consumption (Figure 4).

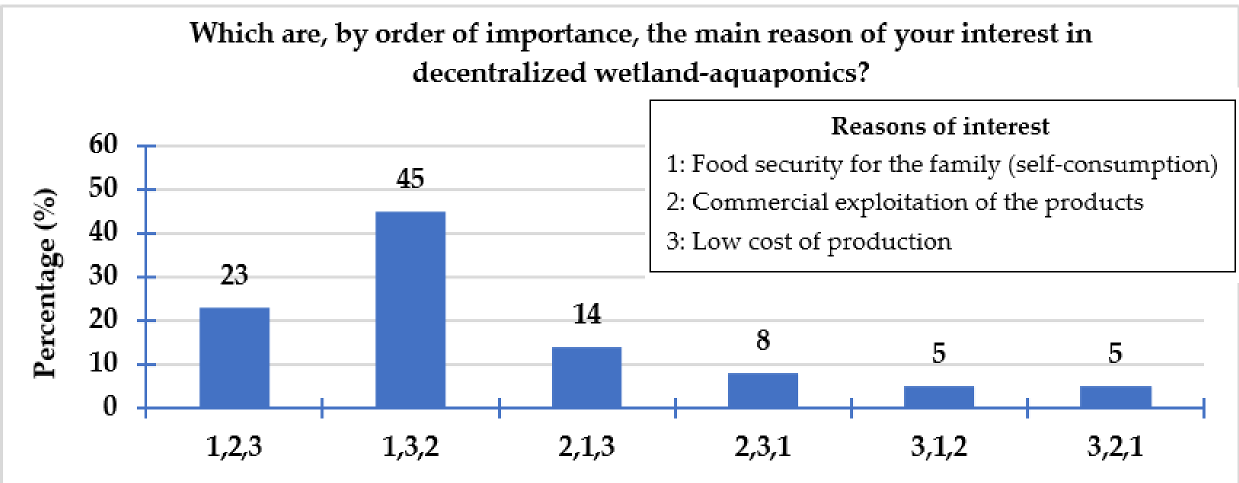

Figure 4. The main reasons of interest in decentralized wetland-aquaponics, according to their order of importance for the stakeholders in Akkar al-Atika. In the y axis, the 3 digits per class represent the order of importance for the stakeholders (first the most important reason and third the least important reason).

This reason has been identified as the first priority (highest importance) for 68% of the stakeholders. For most stakeholders (45%), the first, in order of importance, reason was food security; the second was the lower cost of production that can be achieved using lower inputs of water and fertilizers; and the less important reason was the potential commercial exploitation of products.

In terms of the decentralized implementation model, two equally balanced trends have been identified in the area. On the one hand, 52% of stakeholders prefer cooperative systems operating at the community/neighborhood level that will allow the sharing of workload, risks and profits. On the other hand, 47% prefer slightly smaller systems operating at the household/farm level as an independent family business (Figure 5).

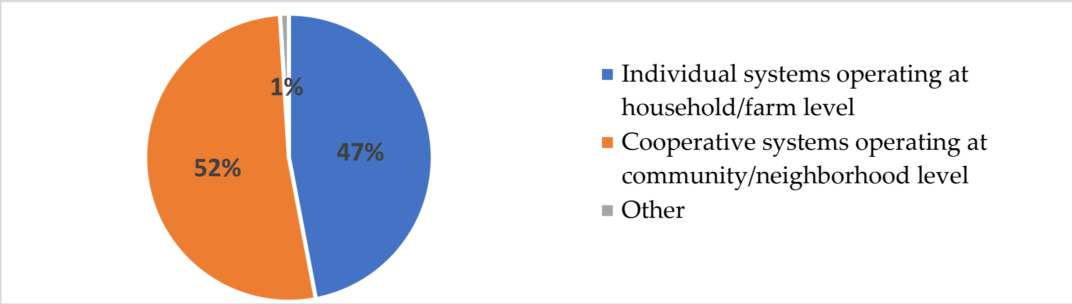

Figure 5. Public perception regarding the most beneficial level of decentralization for the wetland-aquaponics systems Akkar al-Atika.

However, there remain several challenges that need to be addressed at the operational level in order for this technology to be adopted by local stakeholders. In the case of Akkar al-Atika, the vast majority of stakeholders (68%) are mainly concerned about the capital costs of construction, as this is a low-income area. Similar concerns were also reported in a similar study with small-scale farmers in São Carlos, Brazil [20]. Furthermore, the lack of knowledge regarding construction and operation is considered the main difficulty for 35% of stakeholders, while 21% are concerned by the lack of scientific/technical guidance and support (Figure 6). From this perspective, the mobilization and cooperation with administrative authorities, the scientific community, NGOs, market networks and potential investors, the exploitation of financing mechanisms and tools, as well as the promotion of social innovation initiatives, could be explored to address these multidimensional challenges.

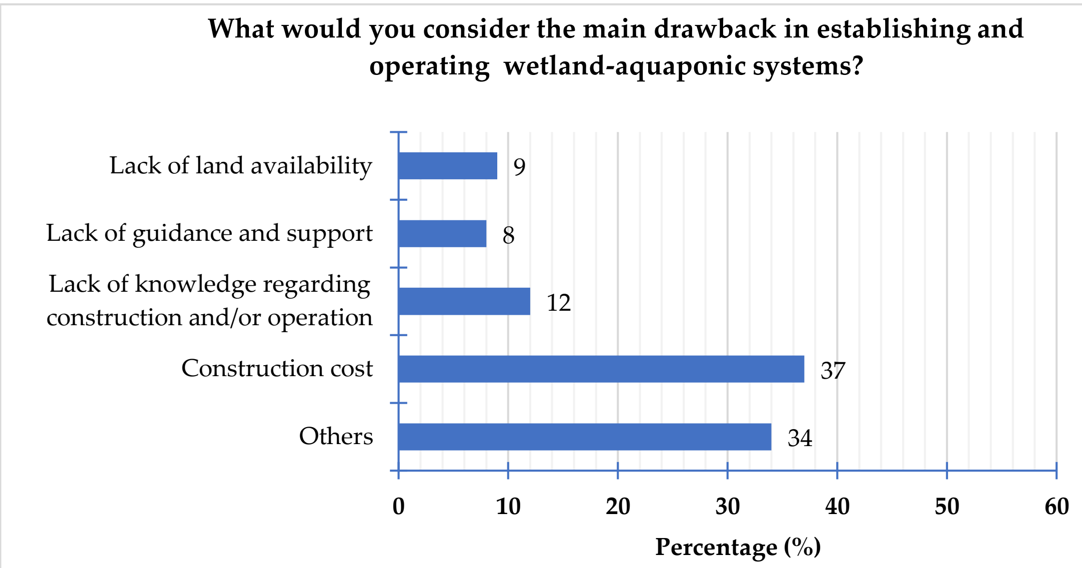

Figure 6. Stakeholders' assessment of challenges/drawbacks for the establishment and operation of decentralized wetland-aquaponic systems in Akkar al-Atika.

4.2. Environmental and Socioeconomic Impact Assessment

The participatory impact assessment is exploring the sustainability of aquaponics considering the environmental, economic and social dynamics [29] through the prism of local society in Akkar-al Atika. From an economic point of view, the initial investment cost is probably the main disadvantage of small aquaponic systems. Beyond this, the systems are usually characterized by low operational costs as well as viable returns from the production and commercial exploitation of fish and vegetables, which is of particular importance for small-income households. In the case of Akkar al-Atika, this is clearly reflected in the public perception of economic benefits since 77% of the stakeholders consider that the establishment of decentralized wetland-aquaponics systems could improve the economy of the area (Figure 7).

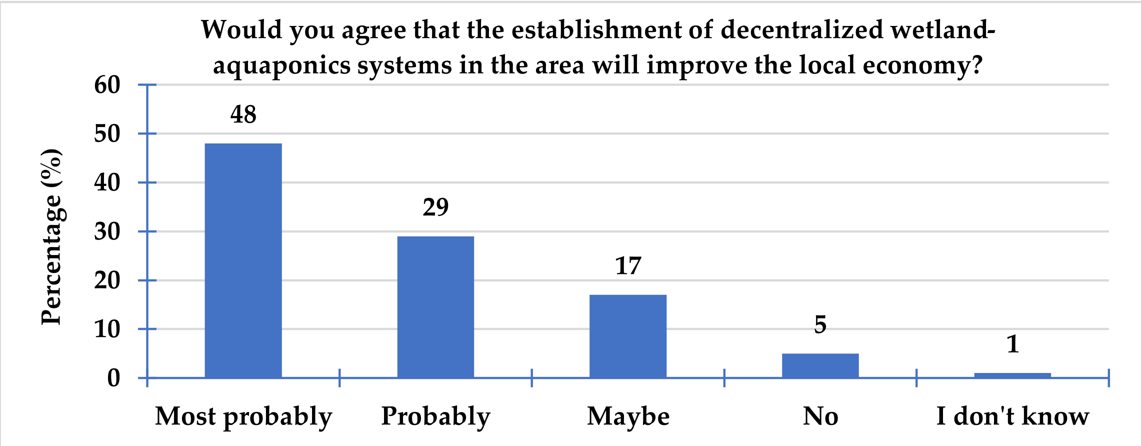

Figure 7. Public expectations regarding the impact of decentralized systems on the local economy of Akkar al-Atika.

The above expectations have been explored through an empirical economic analysis using stakeholders and experts' opinions, for the preliminary assessment of potential economic benefits from the operation of decentralized systems in Akkar al-Atika (Table 1). Running costs are divided between variable and fixed costs. Since the operational cost associated with fish production is quite higher than the cost of vegetable production [30], a higher ratio of plant to the fish revenue model was considered, providing a cost-effective solution for the smallholder operators of Akkar al-Atika. It is assumed that each water pump is working between 10 and 14 h per day and consuming 16 to 18 kW per month, while the air pump working 24/7 consumes about 45 kW per month. Total monthly power consumption is about 100 kW, and 1 kW is rated at 0.1 USD. Tilapia production is estimated to be 10 kg per month, with a mean price rate of 8 USD per kg. The net profit for commercial purposes can reach 255 USD per month, or a yearly profit of 3060 USD, assuming a monthly production efficiency of 95%. However, this high efficiency rate is usually reachable in hydroponic practices. Returning to the objectives that led to this study, small-scale aquaponics is proposed to be decentralized and is designed to help farmers and the rural population. Thus, in the economic model, it becomes more profitable by removing the worker's salary cost (100 USD per month), which leads to an enormous improvement in net profit of about 28%, which becomes 355 USD per month. Thus, for the vast majority of the local stakeholders with low annual income (<600 USD/year for 48% of the population, as mentioned in Section 2), the small-scale aquaponic system may provide a significant increase in their yearly income of at least five to seven times.

Table 1. Empirical analysis of operational Cost and Profit for a mothy production of 770 crops of lettuce and 10 Kg of Tilapia fish.

Cost Per Month in USD		
Variable costs	• Seeds • Germination compost • Fertilizers and nutrients, packaging, * Fish feed for Tilapia • * Tilapia Fish	80 USD/Month
Fixed costs	1 Worker Electricity (15–20 kW)	100 USD/Month 10 USD/Month
	Total cost:	**190 USD/Month**
	Gross profit per month in USD	
Production of lettuce (french lettuce) as lolloroso, lolloverde, oak leaf lettuce (*Lactuca sativa* var. *crispa*) red and green, endive, kale, etc. . .)	Carton trays number to be sold on a on monthly basis: 128 • 6 crops in each carton tray • Sales ratio 95% • 1 head of lettuce 0.5 USD • 3 USD/tray	365 USD/Month
* Production of Tilapia Fish	10 kg of Tilapia fish −1 kg of Tilapia 8 USD	80 USD/Month
	Gross profit:	**445 USD/month**
	Net Monthly Profit:	**255 USD/month**

* The fish feed amount and tilapia production is calculated based on the following data: (1) at the beginning of fish rearing: 200 fish/m^3 are put in the tank (80–100 g/fish, 16–20 kg/m^3, 0.5 USD/fish (2) Feeding: (a) Starting cultivation period <150 g/fish (0.75 kg/day); (b) Mid cultivation period >200 g/fish (1 to 1.2 kg/day); (c) Fast growing period >300 g/fish (1.7 to 2 kg/day), at this stage it is assumed that the rearing tank contains 150 fish having weight greater than 600 g/fish and the 1 m^3 tank has 130 kg of fish. (3) Protein content in fish feed fluctuate between 27 and 35% as a function of the cultivation period. (4) Total rearing cycle is around 6 months.

What remains to be resolved is the problem of the implementation cost of such systems for families having very low incomes. In this context, the intervention of financing programs developed by world organizations, or communal installations, would appear to be realistic solutions.

Environmentally, aquaponics may play a crucial role in the sustainable management of natural resources in Mediterranean watersheds. According to the stakeholders of Akkar al-Atika, the establishment of decentralized systems may benefit both the soil and water resources of the area and thus address multiple environmental challenges that are related to climate change as well as human activities. Specifically, the main potential environmental benefit (Figure 8) identified by 37% of stakeholders is the prevention of soil and water pollution due to closed-loop water treatment and the reduced use of agro-chemicals in food production. As near-zero discharge systems, aquaponics drastically reduces the problem of nutrient and emerging contaminants pollution and runoff from soil-based agricultural systems while preventing the eutrophication and degradation of water resources and thus addressing environmental challenges, which are particularly evident in Mediterranean watersheds and coastal zones [31]. In addition, a significant percentage of stakeholders (30%) anticipate that aquaponics will effectively contribute to the conservation of water due to the recirculation of water and the lower water demand for primary production. The water scarcity problem in arid and semi-arid regions is of primary importance, especially in food production. It is highlighted that in such areas, the water recirculation in aquaponics can reach a water reuse efficiency of 95–99% [32].

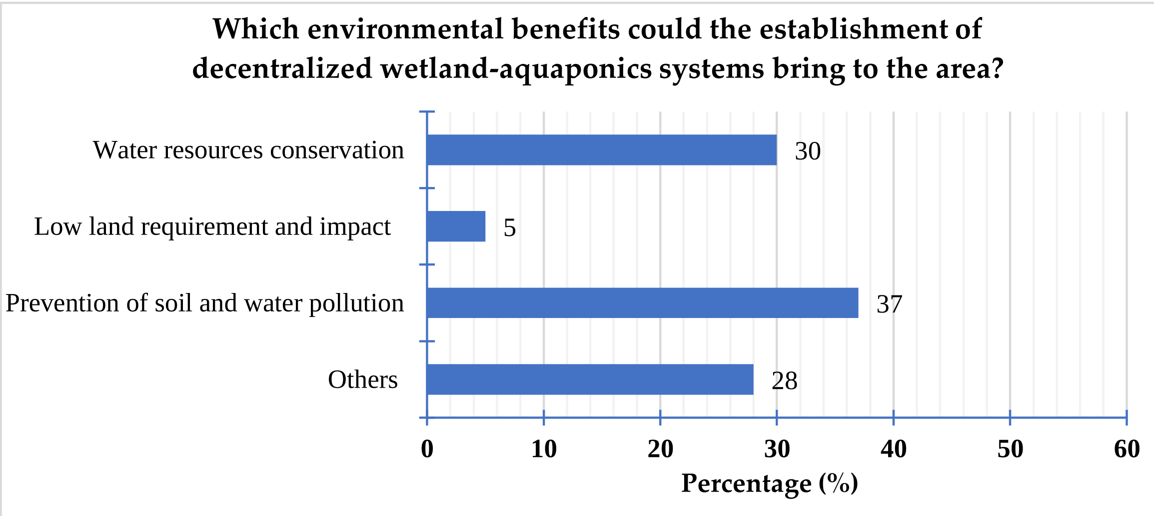

Figure 8. Public perception regarding the main potential environmental benefits of decentralized systems in Akkar al-Atika.

Socially, aquaponics can contribute to the livelihood of societies in disadvantaged areas in multiple ways. In the case of Akkar al-Atika, the potential positive impact on local society has been identified by a vast percentage (95%) of stakeholders (Figure 9), in terms of increased skills and future employment opportunities, green job creation in the area during construction and operation, as well as the willingness to stay in the area and thus prevent the depopulation of Akkar al-Atika.

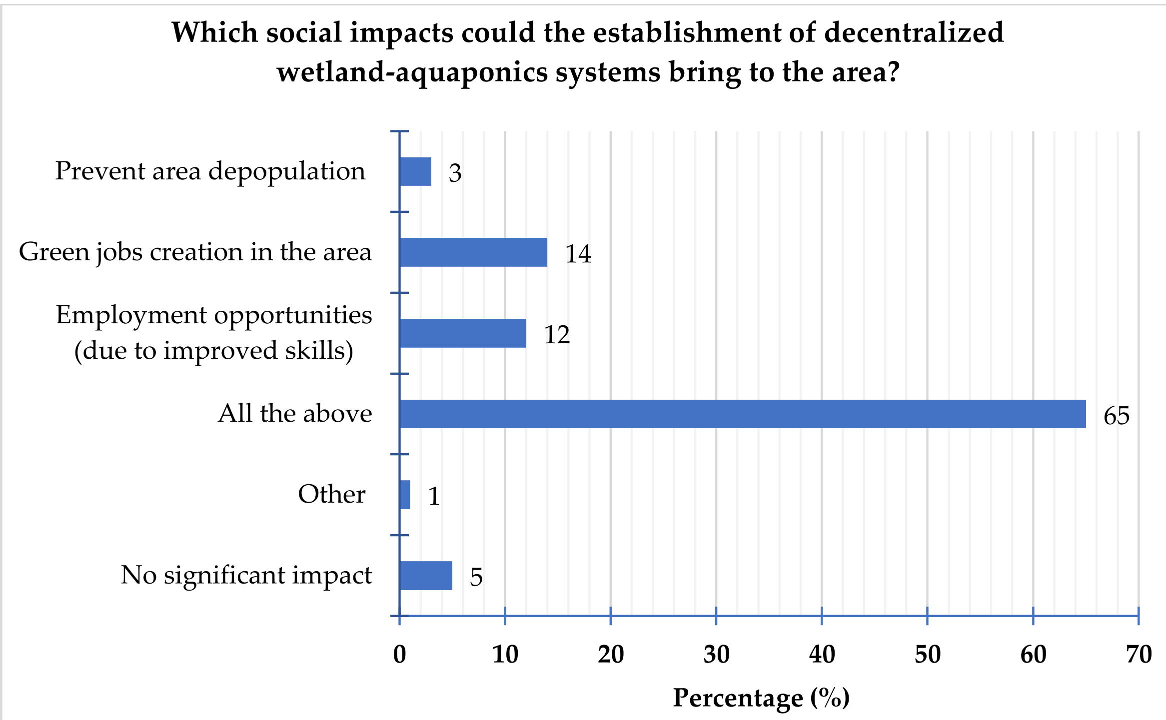

Figure 9. Public perception regarding the main potential benefits of decentralized systems for the local society in Akkar al-Atika.

The food that is grown locally, with culturally appropriate and socially acceptable crops, taking into account the local preferences and characteristics, strengthens the links of ownership and pride between the land, the people and their products. Most important, local food production, along with access to markets and the development of skills, are invaluable tools for promoting the emancipation of women and the empowerment of vulnerable groups of society. In this perspective, the creation of green jobs and the strengthening of employment opportunities for people with increased skills provide a solid basis for fair, equitable, and sustainable socio-economic growth [33].

Furthermore, local society will also benefit in terms of food security and health. In terms of food safety, and given the fact that aquaponics are controlled systems with biosecurity measures, they require far fewer agro-chemicals (e.g., chemical fertilizers and pesticides) for plant production [31], which makes the food safer to consume while safeguarding against potential contamination.

In terms of food security, aquaponics can be considered a constant source of crops (e.g., vegetables) and fish protein throughout the year. Especially the fish protein is a valuable addition to the dietary needs of several people, particularly in remote mountainous areas. More than 47% of the stakeholders in Akkar al-Atika are willing to reduce their meat consumption and replace it with fish protein produced locally (Figure 10), as long as the price of fish is not higher than the price of meat. Such dietary improvement may result in multiple health benefits since fish is considered a primary source of omega-3 fatty acids, while several studies document the lower risk of heart attacks and strokes for people who regularly consume fish protein [34].

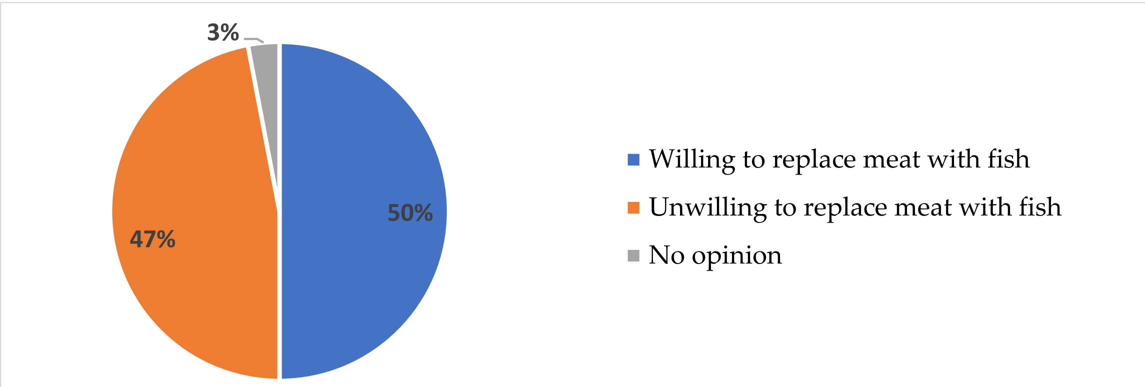

Figure 10. Public willingness of dietary modification, from meat to fish protein in Akkar al-Atika.

5. Discussion and Recommendations

The main challenge for the Akkar al-Atika area was to find an effective way for the customization and introduction of a system that would be able to address key societal challenges and needs in the area. In this perspective, the Living Labs in the open innovation ecosystem of Mara-Mediterra, acted as a participatory mechanism, facilitating stakeholders to: (a) co-create and interact with an operational system; (b) assess the potential and usefulness of such a solution; and (c) transfer their experience to other areas.

The participatory development and evaluation of NbSs, such as decentralized wetland-aquaponics, creates a favorable environment for their adoption and mainstreaming, as the stakeholders are actively involved in the deployment and assessment of solutions that address their needs in a real-life context. The findings of this work address the lack of field evaluations of small-scale aquaponics with constructed wetlands in rural Mediterranean areas. Furthermore, reveal the stakeholder perspectives that provide new insights compared to techno-economic feasibility studies performed by scientists and accredited professionals, which are likely cost prohibitive to marginalized regions and local grassroots initiatives and can have a transformative impact on sustainability [35]. The participatory assessment engages diverse actors in local society in scrutinizing and appraising knowledge on the specific issue. It does not aspire to directly influence political decisions but rather to enlighten them with social values and interests and to accelerate the transition process towards sustainable development with respect to local societies and the environment.

However, it is underlined that decentralized systems may have different economic viability and sustainability implications compared to large-scale commercial aquaponics. Thus, there is a need for more assessments of small-scale decentralized aquaponics installations in real-life settings to evaluate sustainability performance, as well as field testing for the quantification of their environmental benefits (e.g., water conservation).

The case of wetland-aquaponics within the framework of the Mara-Mediterra project illustrates the cross-border cooperation potential of Living Labs in the development of novel as well as practical solutions within a sustainability context. However, implementing a practice such as decentralized wetland-aquaponics, will not be easily affordable for small farmers in disadvantaged rural and mountainous areas. Quantified performance assessment, technical assistance, training programs and financial support are needed to safeguard the successful implementation of such a practice. Investments by local authorities and NGOs are essential companions for starting up low-cost and small-scale wetland-aquaponics systems. It is clear that decentralized small-scale wetland-aquaponics are not miracle solutions for eradicating famine and food security problems, but they may certainly provide access to food both in terms of quantity and quality, increase incomes for farmer families, and promote the empowerment of vulnerable groups of society while contributing to sustainable environmental management by preventing the degradation of soil and water resources, maintaining soil fertility, and reducing the overexploitation of fresh water supplies for crop production in arid and semi-arid climates [36]. The major challenges remain the cost of investment and the energy consumption, which can be reduced by using renewable energy. In this context, the local stakeholders in Akkar al-Atika were skeptical about the investment to be made and the return that they could have. However, they showed enthusiasm regarding the decentralized, small-scale aquaponics implementation if funded and initiated through SDG programs.

Overall, based on the outcomes of the Living Labs and participatory assessment survey and taking into account recent scientific studies [30] as well as the relevant FAO recommendations [29], the potential key factors of success for decentralized systems in disadvantaged areas include:

- Size between 50 and 150 m^2, depending on the preferred level of operation (farm, neighborhood or small community).
- Construction that uses locally sourced materials and workforce to minimize capital costs and maximize green job opportunities.
- Exploitation of harvested rainwater in the production process if and where possible.
- Promotion of energy autonomy through the use of renewable energy sources (e.g., photovoltaics, biogas from waste).
- Use of natural systems and processes for the quality improvement of the recirculated water (e.g., constructed wetlands)
- Efficient management systems that will lower the operational costs while ensuring the delivery of quality products able to satisfy both the consumption needs of the owner as well as the market needs for commercial exploitation of production.
- Mobilization and engagement of local society in demonstration actions through participatory processes of co-design, co-development and co-evaluation of pilot systems (e.g., Living Labs) that will allow the community to embrace and support relevant initiatives for the benefit of the local economy.
- Deployment of a multi-actor cooperation network in and beyond the area, supporting the establishment and operation of the decentralized systems through communication and publicity actions, knowledge transfer, market exploitation, capital leverage, entrepreneurship support, lifelong learning, and skills development.

6. Conclusions

Living labs are participatory platforms that enable the co-creation and co-evaluation of sustainable Nature-based Solutions to address rural challenges in the Mediterranean region. At the local level, Living Labs bring together different actors from the quadruple helix model, such as public authorities, academic institutions, the private sector and civil society, to collaborate on common goals and accelerate the development and adoption of solutions at the operational level. Thus, the Living Labs approach could be expanded to optimize the design of both technological and nature-based solutions, assess their feasibility across different contexts, and promote their mainstreaming. At the cross-border level, Living Labs may play a critical role not only in the cross-fertilization of applied innovations that are aligned with the United Nations Sustainable Development Goals (SDGs), but also in bringing corresponding communities together and contributing to the establishment of bridges between countries and societies that face common challenges. In this direction, the strengthening of cross-border cooperation pathways, especially in Mediterranean, needs to be further enhanced through enabling governance schemes and mechanisms of collaboration.

The increasing environmental consciousness within society, coupled with the progress in Nature-based Solutions (NbSs) and the demand for dependable yet cost-effective solutions, foster a conducive environment for the emergence of decentralized wetland-aquaponic systems. These systems present themselves as an appealing eco-technology capable of effectively tackling environmental challenges and ensuring sustainable food security. However, more real-life assessments are needed to evaluate their sustainability performance. In light of this, it becomes imperative to assess and quantify through field testing both the environmental (e.g., water conservation) and economic performance of these systems in the rural Mediterranean context and enhance their design and construction. This optimization process will unlock their scale-out potential and mainstreaming.

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