EXPLORING THE ROLE OF PUBLIC-PRIVATE PARTNERSHIPS IN ENHANCING SUSTAINABILITY AND DIGITIZATION IN AQUAPONICS: A CASE STUDY OF THE ISEPA PROJECT

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Abstract: Today the sustainability of agricultural production systems is widely recognized as a crucial point for the implementation of long-term economically, ecologically sound and socially acceptable policies and practices. This study investigates the role of the public and private partnership (PPP) in the resolution of problems related to the sustainability of both agricultural processes and food production through the integration of the enabling technologies of Industry 4.0 (IoT, Big Data, AI, etc...). In order to better understand how public-private collaboration influences sustainability and digitisation processes in the primary sector, an analysis of what the literature has identified on the topic was conducted and then an attempt was made to answer the research question posed. Through the case study methodology, the research analyses and promotes the results of the ISEPA project. A research project whose PPP had the joint objective of experimenting with new techniques and integrating modern digital technologies in order to foster the sustainability of farming processes, and in particular to promote the advancement of aquaponics systems by also increasing knowledge of their automation.
Keywords sustainability, public-private partnership, agricultural process, digitalization development

Introduction

Over the 21st century, the agricultural sector has faced rapid evolution involving economic, social and environmental scenarios. Several factors including climate change, urbanisation and industrialisation pose new major challenges for this sector (Tappeiner et al., 2021). In addition, by 2050, the world population is expected to increase by an estimated 9.7 billion (Nikos & Bruinsma, 2012; UN DESA, 2019), prompting the United Nations Organisation to emphasise the important growth in primary and food needs (FAO, 2014). The increase in food demand, together with the transition towards intensive consumption styles of animal-based proteins (in lower and middle-income countries) inevitably leads to the question of the sustainability of agricultural processes, as 50% less fertile soils and scarce water reserves are estimated to be available for almost half of the global urban population (He et al., 2021).

The concept of sustainable agriculture was initially introduced in the publication of the Brundtland Report in 1987, along with the initiation of the idea of sustainable development (Tait et al., 2000; Velten et al., 2015; Porrini & Striani, 2017). Since then, the need for sustainable development that is equitable in both social and environmental terms has been increasingly stressed at the policy level, and it also appears in the SDG 17, which focuses on partnerships, calling for greater cooperation between public, private and third sector organisations to implement sustainable development, particularly within developing countries (Leal Filho et al., 2022). In recent decades, the sustainability of agricultural production systems, together with their evaluation, is considered crucial for the implementation of long-term economically and ecologically sound, and socially acceptable policies and practices (Bartzas et al., 2020). These three aspects are often interconnected, creating a dynamic and simultaneous balance between them (Hayati et al., 2010). However, sustainability is little investigated in the agribusiness sector (Brenya et al., 2022), despite the application of the integrated approach of the Triple Bottom Line model, which claims companies should simultaneously achieve better financial performance, environmental protection goals and equity for the society (Elkington, 1998). This is because many studies are often focused on particular aspects of sustainability, as clearly debated by the existent literature (Forssell & Lankoski, 2015; Maxey, 2006; Michel-Villarreal et al., 2019; De Matteis & Borgonovi, 2021).

In the light of the above, this paper is to investigate the role of PPP application to try solution to the problem of the sustainability of agricultural processes through the integration of the enabling technologies of Industry 4.0 (IoT, Big Data, AI, etc.), in inherently more virtuous production systems such as aquaponics. In a nutshell, aquaponics is an agricultural practice that combines recirculating aquaculture systems (the RAS technology) with growing vegetables above ground (hydroponics) (Joly et al., 2015). Its rapid expansion connotes it as a possible state-of-the-art practice capable of meeting the important challenges of today's world. More specifically, aquaponics uses fish waste as a source of nutrients for plants after treatment, operating as a closed-loop ecosystem for indoor agriculture. To deal with such complex systems, the collaboration of the public and private sectors, referred to in the literature by the acronym PPP, is essential. On the one hand, it allows the pooling of competences in different fields, on the other hand, it distributes the risks related to the investment in research, contributing to the development of innovations consistent with the sustainability objectives of the agri-food sector set in the main policy documents (Agenda 2030, European Green Deal and Farm-to-Fork Strategy).

The paper is structured as follows. After this brief introduction, in the first section we outline the progress made so far while highlighting gaps in the area of sustainability of agricultural processes through PPPs. Furthermore, we will formulate our research question in order to understand the extent to which public-private collaboration and technology can contribute to solving the problems related to the sustainability of food production in the context of overpopulation and urbanisation expected by 2050. In the second section, we illustrate the validity of the single case study methodology as our research methodology, and, in the third section we support the proposed thesis examining the specific selected case study: the ISEPA project. In the last section we report our conclusions.

Theoretical background

The fundamentals of PPPs Subsections

Over time, the public and private sectors have tried to deal with the negative environmental externalities caused by the independent food industry (Martinez-Fernandez et al., 2010). Indeed, in some cases, situations have occurred that have made public-private collaboration inevitable (Ferroni et al., 2011; Moreddu, 2016; Akinwale, 2016). An example of this is the so-called 'Green Revolution', i.e. an initiative promoted by the public sector in the 1940s that however almost completely excluded private sector activities, leading to a general abandonment of appropriate solutions for farmers (Juma, 2010). This example shows how isolated public or private sector interventions alone are unable to address the complex challenges of the 21st century (Melhus et al., 2012), particularly the achievement of a certain degree of sustainability development of agricultural processes. Partnerships between public and private institutions seem to be the optimal solution to overcome these obstacles and have existed for some time in many sectors of the economy (Cheng et al., 2021; Moreddu, 2016).

What has led to the evolution of PPPs is an environment of limited government experience and resources, as well as a lack of facilities, human capital and time (Myrzaliev et al., 2018). In reality PPPs complement scarce public resources (Berisha et al., 2022), facilitate the construction of a more competitive environment, help to improve the efficiency of actions carried out and reduce costs (Paul and Margaret 2003). As Kosinova & Ter-Akopov (2019) state, the cost problem of the latest technologies and structural changes in the economy can be mitigated through collaboration with the private sector. In general, PPPs aim to achieve specific objectives by means of planned proposals and within set timeframes, enabling each partner to deliver projects and services as efficiently as possible (Ponnusamy, 2013). A PPP is in fact based on a cooperative and collaborative contractual arrangement between a public entity (which may be federal, state or local) and a private sector entity (Hodge & Greve, 2007; Marbaniang et al., 2020). Relative to the establishment of a partnership, fundamental factors that lead to a successful partnership must be considered. These factors fall into two categories, namely the characteristics to be sought in the partners, and the essential elements constituting the partnership process (Monaghan et al., 2001). On the one hand, mutual trust between the parties and the compatibility of their organizational cultures represent the filters to be applied in the selection of suitable partners; on the other hand, the detailed and precise division of roles intended for each partner, the sharing of information and objectives to be achieved and the feasibility of the expected timeframes useful for the attainment of these pre-set objectives form the basic steps of the partnership process (Plummer et al., 2022).

In addition to sharing objectives and actions among the partners, regular and mutual information is a prerequisite for building trust. The latter is necessary both for the improvement of performance, and for the continued commitment of the parties involved in the PPP (Panchapakesan et al., 2017). In short, PPPs offer the prospect of overcoming the limitations of each sector: the inherent inability of the business sector to operate where there is no market, and the limited capacity of the public sector to produce market research. In other words, partnerships enable sustainable results that no single party could achieve alone. This can be summarised by stating that the output of a PPP is more than the sum of its parts (Ferroni et al., 2011).

PPPs in the context of modern agriculture

As already mentioned, modern agriculture deals with problems such as climate change, significant loss of biodiversity along with soil degradation, soil compaction, salinisation and pollution, depletion and pollution of water resources, increasing production costs, a decline in the number of farms and, related to this, poverty and a decreasing rural population (Rivera-Ferre et al., 2013). In the form in which it has been practiced and conducted in recent decades, agriculture is itself a major cause of the problems mentioned (Koohafkan et al., 2012). To overcome these obstacles, the introduction of public-private partnerships could be strategic and promote the sustainability of agricultural processes. But, although PPP initiatives are consistently present in the areas of infrastructure development and extension (Lertora et al., 2022), health (Adzhienko et al., 2017), education (Languille, 2017), and construction (Jayasuriya et al., 2019), their application in agriculture is relatively new and scarce (Myrzaliev et al., 2018). Nonetheless, there is a growing awareness of the value of PPPs in the primary sector, particularly for projects benefiting farmers in developing countries and for the sustainability of agriculture processes (Ferroni et al., 2011).

For PPPs to contribute effectively to the sustainability of agricultural production, adequate attention should be paid to governance-related issue within their implementation, as a critical factor on which the success or failure of public-private cooperation may depend (Hayllar, 2010; Ismail, 2013; Debela, 2019; De Matteis et al., 2021). A public-private partnership (PPP) in agriculture is understood in terms of the party sharing ideas and resources, market and technologies, risks and benefits (Ponnusamy, 2013). Indeed, the PPP approach has enabled farmers to improve access to the latest technologies, their progressive development and the market. PPPs represent an advantageous potential for the development of agricultural processes, as they can concretely facilitate and accelerate the advancement of the agricultural sector. Specifically, these collaborations lead agricultural processes towards effective and significant sustainable development, with multiple other benefits attached (Rankin et al., 2016). Thanks to the introduction of PPPs is possible to organise and deliver remarkable and innovative investments (White, 2013). Such investments may stimulate agricultural production, increase the efficiency of the sector, improve cost-effectiveness, as well as expand storage and transport capacity (Myrzaliev et al., 2018), and are deliverable through projects. Clearly, together with the numerous benefits, there are also risks. The introduction of PPPs in the agricultural processing sector highlights problems associated with guaranteeing the supply of raw materials, sourcing arrangements and setting tariffs, thus affecting cooperation and coordination between partners. This can be avoided by delineation of roles and good planning of the operations to be carried out (Bing et al., 2005).

In summary, PPPs in agriculture combine operational and economic efficiency from the private sector, and the role of the public sector as a creator of an environment in which social interests are considered. The combination of both ensures number of potential benefits to support the development of sustainability in agricultural processes and, at the same time, allows for risks that can be shared between the various stakeholders (Rankin et al., 2016). Major challenges such as population growth and competition for resources pose a threat to the food security of the planet. In order to address the ever-increasing complex problems in agricultural production systems, advances in 'smart farming' and 'precision agriculture' offer important tools to address the challenges of agricultural sustainability (Sharma et al., 2020).

Digitization is one of the most important ongoing transformation processes in agricultural processes and food chains at all levels such as production, processing, distribution and consumption (Latino et al., 2022). Various technologies and practices in agriculture, based on Big Data, IoT, AI, can make the right decision at the right time and in the right way. However, the use of such technologies in agriculture and the resulting data is not sufficiently widespread and needs for more investment in the creation of suitable infrastructure, related skills and knowledge of the technology by farmers, attitude of inclination towards the latest technologies and awareness of the benefits of Big Data-based technologies (Sarker et al., 2020). In particular, the farmer needs the help of a team of experts in order to implement the existing dedicated facilities; similarly, the implementation of the technology requires both government initiatives and the involvement of the private sector, hence the need for a public-private partnership (PPP). Such collaboration is necessary because data from agriculture are characterised by large quantities, as they measure several relevant characteristics such as variety, rate of variability and veracity. This mass of data requires an analytical approach and specific technology to be transformed into information ready for use in agriculture.

From an economic point of view, then, the use of PPPs that combine public and private finance brings undeniable advantages. In fact, the economic literature (Leland & Pyle, 1977; Holmstrom & Tirole, 1997; Iossa & Martimort, 2008) suggests that the establishment of a PPP provides a positive signal on the soundness of the project, credibly conveying to third parties that the project is economically viable and the business plan is well formulated: thus, adverse selection problems are alleviated, improving efficiency. Moreover, monitoring can alleviate moral hazard problems and generate efficiency gains that offset the higher cost of private versus public finance. More specifically, it is necessary to understand how technology contributes to the development of agricultural processes. Research and developments in the field of artificial intelligence (Artificial Intelligence, AI) have given birth to Smart Systems. These systems use state-of-the-art information, communication and computing technologies (Ulum et al., 2019). Smart Systems have automated components and use wireless technology. An automated system receives input signals, which are processed and compared with control values (range). Finally, it produces output signals.

The world of Intelligent Systems is also linked to the Industry 4.0 paradigm. This connection broadens the concept of Intelligent Systems, since they contain complex logical processes and algorithms that are not limited to simple basic logical operations. In this context, the term "intelligence" therefore extends the computational capabilities, emphasising the aspects related to the complexity that derive from the connection and integration of various components, which react to stimuli and adapt over time (Butt et al., 2019). An emblematic case is that of Kumar et al. (2016), who developed a wireless aquaponic system: through complex mathematical regression algorithms (models that estimate the relationships between input variables and response variables), it was possible to estimate the future values of some parameters, such as nitrates and pH, following measurements conducted in previous times and acting "in a smart way" on the outputs.

The use of the Internet of Things (IoT) in aquaponic systems can guarantee better environmental and growth conditions for plants and fish, allowing higher yields with a lower expenditure of fundamental resources such as water (Yanes et al., 2020).
In the light of the benefits and shortcomings anticipated above, we intend to answer the following research question:
RQ: "What are the benefits and risks associated with PPPs to support the sustainability of agricultural processes and contribute to their digitisation?".

Research methodology

In our paper we applied the case study approach. This approach has sometimes been criticised for a lack of scientific rigour and poor generalisability, as it may not produce results that are transferable to other contexts (Yin, 2012). Yet, there are several ways to address these concerns, including: the use of theoretical sampling; validation of interviewees; and transparency during the research process (Crowe at., 2011). Basically, within the case study methodology there are two approaches in the literature: single case studies and multiple case studies (Yin, 2012). The latter methodology is particularly suitable for situations characterised by large number of variables, and a high degree of conditioning by the context in which the cases are placed (Gustafsson, 2017). Conversely, the single-case study approach guarantees a rich and holistic account when applied to specific phenomena (Gerring, 2004). Additionally, Bennett and Elman (2010) point out that single case studies are implicitly comparative in that one avoids comparing cases that might represent deviations (deviant cases are defined as those whose outcome does not fit previous theoretical expectations or broader empirical models). A further advantage of the single-case study is certainly that it ensures cost-effectiveness from every point of view (money, labour, time, effort), and it is therefore particularly suitable for a case such as ours, in which the study is inherently costly, as it is based on units that are in themselves complex (Eckstein, 1975).
We therefore opted for the single-case study approach, whose advantages are particularly suitable for the context under analysis. Precisely, the choice of the case study to be analysed was based on both the consistency of the case with the specific variable (transparency during the research process), and the availability of searchable documentation (validation of respondents).
The following table shows the schematisation of the aspects covered.

Table 1. Aspects Schematisation

n.	Aspect investigated	References	Case study choice reasons
1	PPP and sustainability	Ferroni et al., 2011 Myrzaliev et al., 2018 Ponnusamy, 2013 Hayllar, 2010 Ismail, 2013 Debela, 2019	The case study is focused on the impacts that industrial aquaponic has on sustainability

2	PPP and digitalisation	Ponnusamy, 2013 Rankin et al., 2016 White, 2013 Myrzaliev et al., 2018 Bing, 2005	The automation system developed in the case study digitises the process, as it allows the aquaponics system to be remotely monitored and controlled, greatly limiting human intervention.

Source: Own Elaborations

The research design of this paper involves a total of three integrated steps. The sources used to acquire the data in the various steps are:
Analysis of the PPP subject of the case study, with a particular focus on the process sustainability and on the digitalization, elements supported by public-private cooperation. The data source was a documentary analysis (Bowen, 2009) essentially based on the initial project, on some intermediate reports, and on the final report of the analyzed project;
Analysis of the two factors of the PPP's research object using the perspective of a referent from one of the project partners (Chief Scientific Officer, CSO). In this case, the data source was a semi-structured interview (Kvale & Brinkmann, 2009) that explored the main technical aspects relating to the process sustainability, and the integration of digital solutions in the aquaponics system developed by the PPP;
Analysis of the two factors (sustainability and digitalization) in terms of functioning of the governance structure and experimentation with digital devices. Here the data source is the technique of unstructured and disguised direct observation (Bailey, 1994);
Therefore, using this approach, we will examine the project ISEPA's PPP contribution to increasing sustainability of agri-food production.

The Role Of Multidisciplinary Ppps In Supporting Digitization Of Aquaponics Production To Increase Sustainability: The Case Of The Isepa Project

The project "Improving Sustainability, Efficiency and Profitability of Large Scale Aquaponics - ISEPA" was launched in November 2018 and was concluded in January 2021 (27 months). It was granted 1,4 mln euros by the Apulia Region through the ROP Apulia ERDF–ESF 2014-2020 Action 1.6 – lnnoNetwork, a funding opportunity for research organisations and private companies to implement joint innovative projects supporting smart, sustainable and inclusive development of the territory and the local communities.
The project ISEPA aimed to tackle the major challenges of industrial aquaponics through the integration of Industry 4.0 key enabling technologies (primarily the Internet of Things), as well as the development of new farming methods based on the use of innovative biomaterials, and the sustainable exploitation of fish-derived food waste (i.e. skin).
According to the project, the study of this agricultural practice's potentials, obstacles, and limitations served as the basis for the research. "The advantages of aquaponics in terms of productivity and efficient use of resources are huge, at least in theory." - the CSO explained at the beginning of the interview. "TAs the European Parliament Research Services listed, aquaponics as one is one of the "ten technologies which could change our lives." - the CSO added, referring to what was stated by Van Woensel & Archer (2015). However, being a rather novel technology, commercial aquaponic production in Europe is still very limited, and very few companies are economically viable (Turnsek et al., 2020).

The current literature on commercialisation of aquaponics in fact identifies three main areas of challenges for aquaponics on a commercial scale: technical (resulting from the integration of two different food production technologies), socio-ecological, and economic (linked to the low competitiveness and profitability of aquaponics food production) (Turnsek et al., 2020). Therefore, reflecting the competences of the public-private scientific-technological organisations involved in the project (see Table 2), research largely focused on the technical issues related to aquaponics system complexity, and the ecological and economic aspects of production. Optimising large-scale production, easing operations in both the aquaculture and hydroponic subsystems to reduce dependence on personnel on permanent stand-by, improving animal welfare as well as the quality of aquaponics food produce, and recycling fish-derived waste were therefore amongst the major strategic objectives pursued by the PPP. Accordingly, the project research activities included:

The definition of an aquaponics system requirements for indoor production of organic fish and vegetable;

Design, prototyping and test of a modular, automated, reduced-environmental impact aquaponics system (compliant with the technical and safety requirements determined above);

The development of new food (raw/processed aquaponics-derived fish and vegetable) and non-food products (type 1-collagen from fish food waste).

At the end of research, the PPP delivered the prototype of an automated aquaponics system allowing the combined farming of Apulian-naturalised Nile Tilapia and local vegetable varieties indoors. The ISEPA prototype integrates 1) an automation system based on an IoT network of sensors, a Decision Support System (DSS), and actuators for remote monitoring and control; 2) a super absorbent natural-based polymer selecting nutrients for plant roots in their growth bed; 3) enriched fish feed to raise quality standards of fillets (primarily nutritional features) and fish-derived food waste; 4) extraction process of highly pure/soluble collagen from farmed fish skin for medical, nutraceutical and cosmetic applications.

Composition and governance aspects of the ISEPA PPP

The ISEPA PPP grouped research organisations and private companies with technical expertise in the core domains of the project (such as System Automation, ICT, Biomaterial Engineer and Biotechnology) but no or little experience with aquaponics.

As it has emerged during the interview with the CSO, "although they (the organisations involved in ISEPA) agreed on the potentials of aquaponics, none of them would invest in this technology individually - because of system complexity - and without any economic support of public entities to partially cover the risks of research."

As a result, based on a bottom-up approach to identify the suitable skills to carry out the research activities, the PPP was built as follows:

1 University Department of Engineering for Innovation;

2 National Research Council's Institutes (Institute of Crystallography, and Institute for microelectronics and microsystems);

6 SMEs engaged in the fields of ICT, biotechnologies, sustainable fish and aquaculture, hydraulics, environmental management and energy efficiency.

Following, the project activities were adjusted to the available skills and the corresponding estimated budget.

Table 2. Partnership composition

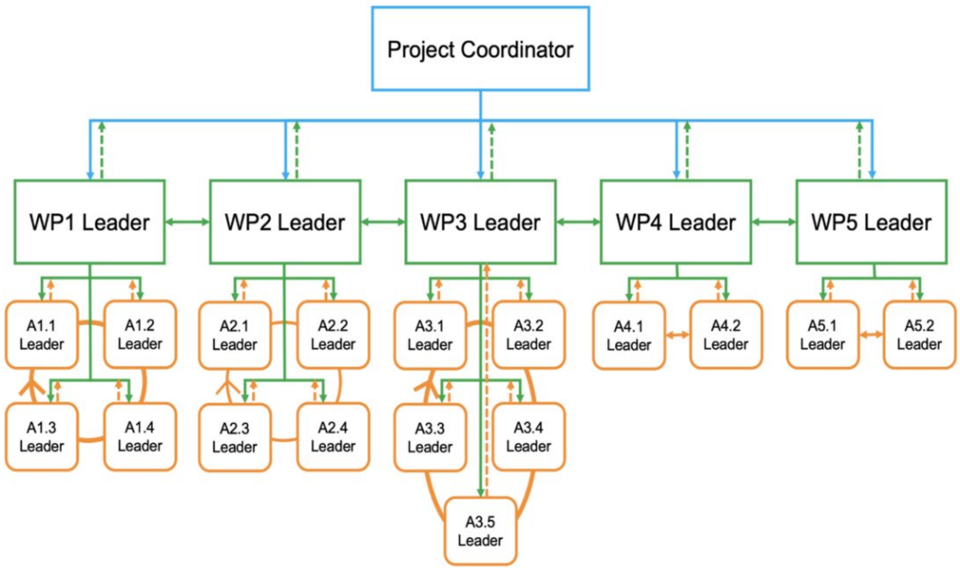
PARTNER'S NAME		TYPE OF ORGANISATION	MAIN CONTRIBUTION TO THE PROJECT
Extended	Short		
Xenia Network Solutions S.r.l. (Xenia)	Xenia	SME	Development of the Decision Support System (DSS)
Naica Società Cooperativa (Naica)	Naica	SME	Application of Business Process Management methodologies to the aquaponics company
Typeone Srl (Typeone)	Typeone	SME	Extraction of collagen from fish skin
Società Cooperativa HYDRA (HYDRA)	HYDRA	SME	Enrichment of quality characteristics of fish and their derivatives
SAMIT TECNOLOGIE s.n.c. di A.L. Mancarella & C. (SAMIT)	SAMIT	SME	Construction of the aquaponics pilot plant
Studio SIGMA S.r.l. (SIGMA)	SIGMA	SME	Cultivation of plants based on alternative substrates (hydrogel plus filtered water from the fish tanks)
Dipartimento di Ingegneria dell'Innovazione – Università del Salento (DII-UniSal)	DII-UniSal	University	Definition of the aquaponics system requirements Implementation of the automation system (IoT network of sensors and actuators) Development of a super absorbent natural-based polymer (hydrogel) selecting nutrients for plant roots in their growth bed
Consiglio Nazionale delle Ricerche - Istituto di Cristallografia (CNR-IC)	CNR-IC	Public Research Organisation	Characterisation of collagen from fish skin
Consiglio Nazionale delle Ricerche - Istituto per la Microelettronica ed i Microsistemi (CNR-IMM)	CNR-IMM	Public Research Organisation	Application of continuous Volatile Organic Compound (VOC) monitoring system

Source: Own Elaborations

In addition to having minimal knowledge of aquaponics, the majority of the private partners lacked experience in managing complex research projects. In order to prevent even the smallest failure, during the project's start-up phase the Project Coordinator thus proposed a stronger and more effective governance structure than was originally intended. This enabled the PPP to obtain the expected results within a reasonable timeframe and given the approved budget. The interviewee stated in this regard: "The success of ISEPA was largely due to the integration of the available knowledge and experience within a public-private scientific-technological partnership, governed by a precise structure."

Contrary to the project plan, the Partners of ISEPA actually adopted a governance structure consisting of three main bodies: the Project Coordinator, the WP Leaders and the Activity Leaders (Figure 1).

Figure 1. Governance structure



Source: Own Elaborations

The Project Coordinator centralised the overall planning, management and control of ISEPA. He was in charge of implementing the administrative and financial monitoring plan, in order to ensure that time and cost parameters were respected. He also dealt with risk management, to avoid or eliminate causes of non-conformities or other undesirable situations. "Thanks to his personal skills and knowledge of all the partners involved, the Project Coordinator could mediate between the different positions and views smoothly. This allowed him to optimise the general organisational aspects even during the period of uncertainty in the early months of the Covid-19 pandemic." - emphasised the interviewee. Finally, the Project Coordinator was assigned the task of supervising the communication and dissemination activities - though the scientific dissemination of project results was arranged in a separate plan and addressed to the research organisations within the Partnership.

On the contrary, the WP Leaders and the Activity Leaders were responsible for organising the research activities, setting the quantitative and qualitative objectives of the methodological and technological activities, monitoring and reporting on the progress of the project to the Project Coordinator. WP and Activity leadership was attributed according to knowledge and/or previous experience in the field owned by the Partners. "Actually, the competences of each partner played a decisive role also in the maintenance of a stable

governance structure supporting the achievement of the project sustainability objectives." - the respondent added during the interview.
The three bodies interacted regularly during the project, and they intensified communication throughout the Covid-19 pandemic to complete research without interruption. When the use of teleconference platforms proved to be insufficient to guarantee the continuation of the test phase, the Project Coordinator and the WP Leaders agreed to grant greater decision-making authority to the academic partner. Therefore, the governance structure they built proved to be a critical factor for the success of their cooperation, as confirmed by the literature (Hayllar 2010; Ismail 2013; Debela 2019; De Matteis, 2022).

DISCUSSION

Digitization of aquaponics processes
Another interesting aspect according to the purpose of this study is the contribution of the ISEPA PPP to the digital transformation of aquaponics. Traditional systems heavily depend on the availability of skilled labour to operate fish farming and soilless cultivation of plants, while preserving their mutual equilibrium. Particularly, to ensure quick response to pests and disease, and also because of strict animal welfare regulations, the system requires alarm protocols and personnel on permanent stand-by (Turnsek et al., 2020). This translates into higher operation costs that add to income losses due, precisely, to fish or plant diseases or pests, or system malfunctions (Savidov & Brooks, 2004). Conversely, the automation system developed by the ISEPA PPP allows for remote monitoring and control over the aquaponics system, limiting human intervention likely only to extraordinary repairs. On the one hand, the IoT infrastructure constantly checks water quality and environmental parameters (pH, temperature, dissolved oxygen, redox potential, concentration of nitrites, nitrates and ammonia and VOC levels); on the other side, the actuators automatically adjust settings (e.g. electrovalves and water pumps), in case of parameters outside of range (such as an increase in the levels of pH or temperature). In addition, controllers manage the protocols and peripherals used in the aquaponics plant and make the system "smart". Finally, the DSS provides users (or operators) with a series of data analysis functions and models in an interactive way, thus increasing the decision-making process efficiency and effectiveness, likewise the plant management. For example, if one or more parameters exceed pre-set threshold values, an alarm system promptly warns users who can take action to bring the situation back to normal. Indeed, this automation system offers further advantages in terms of efficient use of water and enhanced food quality. Quoting the interviewee, "continuous control over the production environment enables to maintain aquaponics' parameters in the optimal ranges, hence reducing water disposal and replacement. In addition, it allows minimising fish health risks thus ensuring the quality of the products." Accordingly, the ISEPA automation system realises both the stable and healthy growth of fish and vegetables (which in turn results in higher yields in the face of lower operating costs), and the lowest possible water and energy consumption.

The ISEPA PPP contribution to increasing the overall sustainability of aquaponics
A final aspect to be investigated is the impact of research on the overall sustainability of industrial aquaponics. As clearly emerges from the previous paragraphs, all four major

innovations developed by the ISEPA PPP enhance the environmental, economic and social sustainability of industrial aquaponics. For example, both the automation system, and the hydrogel-based farming method positively affect the use of water (the latter by boosting the filtering power of plants). Moreover, the sustainable exploitation of farmed fish skin allows for recycling fish-derived food waste, while providing aquaponics farmers with an additional source of income. Finally, the ISEPA automation system also has a positive impact on farmers whose workload is reduced, and who can benefit from stable and more competitive food production. In conclusion, "the project ISEPA has enabled the partners to direct their digital capabilities towards improving aquaponics from several perspectives. Indeed, the current systems could hardly meet the challenges of food security in a changing scenario of increasing and urbanizing world's population. Conversely, the project ISEPA allowed the integration of new frontier and process technologies, which concur to overcome the technical limits of large-scale aquaponics and boost its potential and sustainability." - the respondent highlighted. This confirms the findings of the academic literature, namely that the digitization of the agriculture sector has the potential to increase food production sustainability, through the integration of the different skills of the various public and private partners involved in the innovation process.

Conclusions

PPPs have been widely used in many sectors of the economy for quite some time. However, it is only in recent decades that they have also found increasing adoption in the primary sector (Myrzaliev et al., 2018). In this context, the joint purpose between public and private is mainly to foster economic, social and environmental sustainability in agriculture, along with the need and desire to jointly address the complex problems and digitalization process of agricultural production systems worldwide (Rankin et al., 2016). In fact, today more than ever, the challenges related to agricultural sustainability are closely linked to both economic, social and environmental factors as well as technological factors, such as the use of sophisticated hardware and software tools of intelligent and precision agriculture (Sharma et al., 2020). Using the single case study methodology, this study analyses and promotes the results of the project ISEPA. A research project whose PPP had the joint objective of experimenting with new techniques and integrating modern digital technologies, in order to foster the sustainability of agricultural processes, and particularly to promote the advancement of aquaponics systems by also increasing knowledge of their automation.

One of the successful aspects of ISEPA PPP lies in the project's governance structure. It fostered the processes of cooperation between partners and discussion with project stakeholders and facilitated the continuous monitoring and mitigation of project risks, from the project start-up to project closure. Consequently, the governance model enabled the project results to be achieved on time and on budget. A further strength of ISEPA was the pooling of knowledge and expertise (including systems automation, materials engineering and biotechnology) of various public-private actors, such as research centres and enterprises, with strategic interests in the field of aquaponics. ISEPA's PPP contributed to increasing the level of digitization of the aquaponics systems. In fact, as part of the project, an autonomous system was designed and implemented that allows remote monitoring and control of the entire aquaponics system. The developed system only requires human intervention for extraordinary maintenance activities. It therefore ensures the healthy and sustainable growth of plants and fish with reduced operating costs and reduced use of energy and water.

The project ISEPA is a clear case study that show how PPPs can concretely support the sustainability of agricultural processes. Project results increase the efficiency of plant and animal protein production compared to traditional agricultural and fish production, reducing the use of resources (economic, material and environmental). Therefore, the project ISEPA is a demonstration of how the integration of the competences of different public and private partners can develop innovations consistent with the sustainability goals of the agri-food sector and contribute to the digitization process of the agricultural sector. Thus, a virtuous use of PPPs in the primary sector makes it possible to increase the efficiency and sustainable production of healthy food, as well as to contribute to the resolution of problems related to the sustainability of agri-food production (Leal Filho et al., 2022). However, some critical aspects affecting the replicability of good PPP practices in agriculture as in the present case study should be highlighted. These can be traced back to the need for involving public or private actors with advanced technical and technological knowledge and skills in the PPP. This limits the replicability of ISEPA's PPP to specific technical and economic contexts. Indeed, the case analysed may not be easily replicated in countries where, despite high agricultural vocation, both public and private actors do not have sufficient economic, technical and technological resources of their own. That is the case of less developed countries (Berisha et al., 2022; Juma, 2010). In such contexts, the creation of PPPs capable of making a significant impact on the digitization processes and the sustainability of agricultural production requires the use of capital and knowledge belonging to public and private actors from more developed countries.

A further limitation, to be understood as a possible future research development, lies in the absence of significant institutional partners in the PPP (such as national governments and international organisations in the sector). Their direct involvement may actually facilitate the regulation of the aquaponics sector (Joly et al., 2015), and in particular its digitization processes (including aspects of cybersecurity and data exchange along the supply chain). Consequently, this could stimulate the use of automated aquaponics systems on a larger scale, and positively affect the resolution of problems related to the exploitation of natural resources, and the sustainable production of agri-food commodities worldwide.

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