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Integrated crop-livestock-aquaculture farming systems: Synergistic approaches for balancing agriculture's biophysical requirements and environmental supply: A systematic review

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ABSTRACT

Integrated farming systems are an alternative development strategy for increasing environmental resilience against soil degradation, environmental pollution, and climate change. These different forms of environmental degradation distort the basis of agricultural production through their multidimensional effects. Integrated agricultural systems strategy helps to enhance farmers' socio-ecological capacities to sustain their livelihoods. Therefore, farm management systems, based on the integration of key components of agriculture such as crops, livestock and aquaculture, is the most advanced paradigm of sustainable agriculture. Integrated agricultural system is essential to address the multiple needs of the producer households, such as food security, income safety, and sustainable management of production factors. Managing these major agricultural components separately results in a decline of quantity and quality of expected ecosystem services. It is widely recognized that the single-component approach is not sustainable due to unpredictable and highly dynamic environmental conditions, which, in most cases, are linked to various risk factors. Optimal functioning based on multiple interactions of integrated agricultural systems components has significant potential to contribute to the environmental resilience of smallholder farmers. The aim of this study is to strengthen the understanding on effectiveness of integrated farming systems (crop-livestock and crop-aquaculture) as key tools for balancing agriculture demand and environmental supply. Research provides substantial proof on the beneficial effects of such resilience strategies. This paper, therefore, assembles knowledge over the last decade (2012-2022) on integrated crop-livestock farming system (ICLFS) and crop-aquaculture farming systems

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(ICAFS) in enhancing producers' resilience against soil fertility degradation, climate disturbances and agricultural water crisis and discusses their potential for sustainability. The paper also sets out prospects for improving these farming systems to provide support to farmers and farmer-support structures for a successful agroecological transition worldwide, particularly in Africa.

Keywords: agricultural policies, food security, environmental dynamics, rural development, sustainability, vulnerability.

RÉSUMÉ

Les systèmes d'agriculture intégrée sont une stratégie alternative de développement pour accroître la résilience environnementale contre la dégradation des sols, la pollution environnementale et le changement climatique. Ces différentes formes de dégradation environnementale perturbent la base de la production agricole par leurs effets multidimensionnels. La stratégie des systèmes agricoles intégrés aide à renforcer les capacités socio-écologiques des agriculteurs pour soutenir leurs moyens de subsistance. Par conséquent, les systèmes de gestion agricole, basés sur l'intégration des composantes clés de l'agriculture telles que les cultures, l'élevage et l'aquaculture, constituent le paradigme le plus avancé de l'agriculture durable. Le système agricole intégré est essentiel pour répondre aux besoins multiples des ménages producteurs, tels que la sécurité alimentaire, la sécurité du revenu et la gestion durable des facteurs de production. La gestion séparée de ces principales composantes agricoles entraîne une diminution de la quantité et de la qualité des services écosystémiques attendus. Il est largement reconnu que l'approche à composante unique n'est pas durable en raison des conditions environnementales imprévisibles et hautement dynamiques qui, dans la plupart des cas, sont liées à divers facteurs de risque. Un fonctionnement optimal basé sur les interactions multiples des composants des systèmes agricoles intégrés a un potentiel significatif pour contribuer à la résilience environnementale des petits agriculteurs. L'objectif de cette étude etait de renforcer la compréhension de l'efficacité des systèmes d'agriculture intégrée (culture-élevage et culture-aquaculture) en tant qu'outils clés pour équilibrer la demande agricole et l'offre environnementale. La recherche fournit une preuve substantielle des effets bénéfiques de telles stratégies de résilience. Cet article rassemble des connaissances acquises au cours de la dernière décennie (2012-2022) sur les systèmes de culture-élevage intégrés (ICLFS) et les systèmes de culture-aquaculture (ICAFS) dans l'amélioration de la résilience des producteurs contre la dégradation de la fertilité des sols, les perturbations climatiques et la crise de l'eau agricole et discute de leur potentiel pour la durabilité. L'article expose également les perspectives d'amélioration de ces systèmes agricoles pour fournir un soutien aux agriculteurs et aux structures de soutien aux agriculteurs pour une transition agroécologique réussie dans le monde entier, en particulier en Afrique.

Mots-clés: politiques agricoles, sécurité alimentaire, dynamique environnementale, développement rural, durabilité, vulnérabilité.

INTRODUCTION

Agriculture is a prominent sector for community welfare. This prominence is related to its far-reaching effect on food security, fight against unemployment and poverty (Mugumaarhahama *et al.,* 2020). In rural areas, agriculture is the main source of food, income, employment and socio-professional and cultural stability. Consequently, any factor constraining agricultural production is highly detrimental to human life, especially in rural areas, where access to welfare factors is limited compared to urban areas (Berre *et al.,* 2017).

Farming activities evolve under absolute dependence on biophysical environmental factors. This dependence exposes agriculture to "vulnerability episodes". This vulnerability is due to imbalances between environmental supply and agricultural needs. In such contexts, any change in environmental parameters related to agricultural production affects both quality and quantity of agricultural products. The situation also affects ecological services provided by agricultural systems to different environmental components. Indeed, climatic disturbances and soil degradation are the most advanced forms of environmental alterations, which distort the biophysical basis of agricultural production (Quynh and Kazuto, 2018).

However, the risk factors are more intensified in the absence of the integration between crops and livestock or crops and fish production systems. In such specialized systems, the environmental pollution due to poor management of crop and livestock residues increases, and in the absence of a mineral recycling system, there is a quantitative introduction of chemical inputs into these systems (Paramesh *et al.,* 2019). The situation generates emissions contributing to greenhouse gases responsible for the global warming. The social conflicts between producers regarding the management of production factors, and the high cost of farm management in terms of fertilization and waste disposal are added to this constraint (Zamuluku *et al.,* 2019).

In contrast, in mutualistic systems, due to risk redistribution and synergy of ecological functions provided by different systemic components, an attenuation or absorption of possible environmental shocks occurs; thus, some structural and functional stability is created in such synergy (Lemaire *et al.,* 2014). For instance, on damaged and infertile soil, nutritional shocks are created that disturb plant growth, resulting in lower yields (Alary *et al.,* 2020). Whereas, integrating plants with livestock provides organic compounds to soil through animal droppings.

The incorporation of these organic compounds into the soil is an important basis for restoration and conservation of soil fertility for sustainable plant nutrition, as a consequence of significant biomass production (Mabhaudhi *et al.,* 2019). The useful parts of this plant biomass will be utilized for human consumption and the non-useful parts, which are crop residues, will be used for animal feed. A cycle of by-product valorization is thus established between crop and animal production. Therefore, it is necessary to underline that even forage crop production is effectively supported by an efficient soil fertility management system, which is still clear evidence that the integrative model balances environmental supply and plant needs (Bommarco *et al.,* 2013).

Along the same idea, several studies including Zougmoré *et al.* (2016), Limbu *et al.* (2017) and Othman *et al.* (2019) showed the significance of integrating fish production with plants on water use efficiency, soil and pond fertility management, diversification of food availability, waste management, fish pond productivity and finally on farmers' income.

The pond is a suitable site for nutrient and waste recycling without creating problems related to solid fertilizer degradation (Limbu *et al.,* 2017). Pond water and sediment are used for plant irrigation and fertilization, and plant residues are used as fish food. The integration of plants with aquaculture provides opportunities for increased employability and income for producers, efficient management of crop by-products, and efficient use of water as a valuable and scarce resource (Shoko *et al.,* 2019). These different interactions improve environmental efficiency of input use in both crop and fish production, effectively contributing to the stability of these ecosystems.

However, overall, a low level of crop-animal and crop-aquaculture integration has been observed worldwide over the last decade. The limited level on integration is mainly attributed to the pressure by expansionist systems that support the removal of integrated systems as well as limited and increasingly masked knowledge on integrated farming systems' contribution to environmental stability. We record also the lack of a theoretical framework that highlights key lessons from research on integrated farming systems during the last decade, where environmental disruption is intense, but also the lack of a synergistic research model with an action research format on integrated systems (Behera and France, 2016; Chen *et al.,* 2019; Singh *et al.,* 2020).

It is, therefore, necessary to reinforce understanding of these systems by highlighting the principles and evidence that establish their contribution to improving the balance between environmental supply and agricultural requirements (Alary *et al.,* 2020). The objective of this review is to highlight, through an analytical approach, the effectiveness of integrated farming systems (crop-livestock and crop-aquaculture) in environmental resilience over the last decade. This review is focused on the following question: How does integrated systems crop-livestock and crop-aquaculture balance environmental supply and agriculture's biophysical requirements?

To address this issue, the paper, therefore, assembles knowledge from scientific publications, over the last decade (2012-2022), on ICLFS and ICAFS in enhancing producers' resilience against soil fertility degradation, climate disturbances and agricultural water crisis and discusses their potential for sustainable food production. The paper also sets out prospects for improving these farming systems to provide support to farmers and farmer-support structures for a successful agroecological transition worldwide, and particularly in Africa.

The census of processed articles was conducted using the Web of Science - Clarivate Analytics platform (https://webofknowledge.com/). The combined terms (systems * integrated * agriculture / crop * livestock) and (systems*integrated*agriculture/crop*aquaculture) were used. These terms were chosen because they are included in the subject area. Using the above-mentioned term combination, this initial search generated 117 articles, to which was added 23 articles directly retrieved in google scholar from authors whose profile was deemed honorable. Thus, 140 articles were identified. After this step, 45 of them were excluded, resulting in final 95 articles selected for individual reading and analysis in this review. The reasons for exclusion of the 45 articles were the following: (i) year of publication (before 2012); (ii) the study was based only on socioeconomic issues; (iii) there were no results directly highlighting the link between the ICLFS/ICAFS and soil fertility decline and climate change. Others reasons were iv) the missing link between these systems and soil fertility, sustainable water management, productivity (fish and plant) and climate change; and v) The study directly integrates all three systems (crop-livestock and aquaculture). In addition, the following information was collected manually by analyzing each publication: (a) the country in which the main author originated for review articles; (b) the country in which the study was conducted for research articles; (c) the research goal; and (d) the key lessons learned.

INTEGRATED CROP-LIVESTOCK FARMING SYSTEMS (ICLFS)

Basis and principle. The theoretical approach developed for analyzing and understanding ICLFS establishes both the metabolic processes (nutrient and energy inputs and outputs) and the ecosystem services in agricultural systems (figure 1). ICLFS is an agricultural paradigm that agronomists have developed to intensify crop and livestock systems. The model suggests utilizing by-products from one system as inputs for the other (De Moraes *et al.*, 2014). This approach is based on the use of animal power, organic manure and fodder production, and the reuse/recycling of crop residues for animal feed.

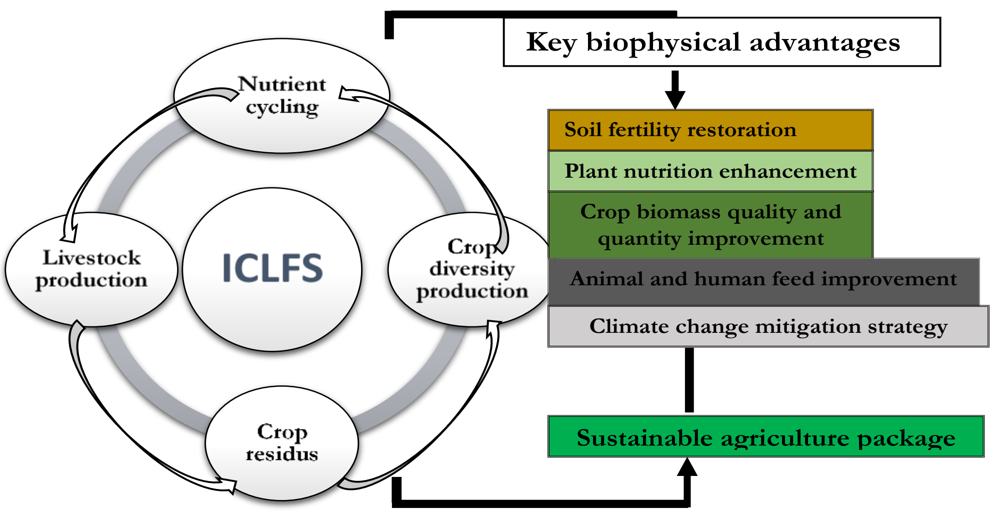

Figure 1. Framework of Integrated crop-livestock farming system and key biophysical advantages

Furthermore, it is recognized that farming systems based on low diversity and high openness to external inputs offer less resilience to potential biophysical risks and contribute significantly less to food and socioeconomic sovereignty (Teka and Walday, 2020). It may also be noticed that these farming models do not promote efficient use of production factors and, therefore, are not a sustainable model for rural communities (Ragassa *et al.*, 2015). However, based on diversity, integration, endogenous knowledge and recycling nutrients to promote self-functionality of agricultural ecosystems, agroecological guidelines including crop-livestock interaction offer alternatives to explore for sustainable agricultural systems (Duncan *et al.*, 2013).

These alternatives hold potential of reducing the impact of productivist systems and the use of chemical inputs on biophysical, human and socio-economic environments (Mackenzie-Tsedi *et al.,* 2020). ICLFS respond to the challenges of sustainable soil fertility management, environmental pollution and climate change, as well as to production factor efficiency (Wiese *et al.,* 2012). Through imitating the nature, these systems strive for self-reliance in agricultural ecosystems by limiting the use of external products (Bonoudo *et al.,* 2014). They advocate cyclical reuse of systemic byproducts and evolved nutrient recycle.

INTEGRATED CROP-LIVESTOCK FARMING SYSTEM STRATEGY FOR SUSTAINABLE SOIL MANAGEMENT

According to Ryschawy *et al.,* (2012), ICLFS enhances existing synergies between cropping systems (forage production, symbiotic nitrogen fixation and mineral recycling) and livestock systems (organic manure and energy production) to reduce fuel, chemical fertilizers and feed intake. It is noteworthy that soil degradation is a major constraint in agricultural areas; the environmental supply being limited by a shortage of nutrients, while the demand (crop requirements on soil properties) remains consistently high. Therefore, agricultural technologies aligned with the sustainable management of this issue are an effective strategy to improve productivity and household livelihoods (Salton *et al.,* 2014). The implementation of agricultural policies that support the integrated crop-livestock farming system for sustainable soil fertility management is essential for the success of a sustainable agriculture. Several authors have reported the ICLFS as a sustainable strategy for soil fertility management. Similarly, many studies support the effectiveness of integrated farming systems versus industrialized or more productivist systems (Table 1). Efficient livestock management produces manure, which is an important organic component for soil fertility. Manure as an organic matter has intrinsic properties to correct soil organic stock, improve soil mineral reserve, and correct soil biological as well as physical properties. Many studies under various environmental conditions indicated that farmyard manure supply improved soil three-dimensional properties, which significantly improved crop yields (De Moraes *et al.,* 2014; Peterson *et al.,* 2020; Patel *et al.,* 2020; Ndjadi *et al.,* 2022). ICLFS allows obtaining manure, which is the result of mixing trampled straw and animal waste. This product allows efficient recycling of mineral elements that are more concentrated and assimilated by plants. The principle of sustainable fertilization is based on feeding soil first, feeding plant later, and not feeding the plant directly through soluble fertilizer (Ferguson and Lovell, 2017). Therefore, manure effectively contributes to the constitution of the soil organic matter stock, the basis for sustainability of the soil fertility. Indeed, for the biological dimension of soil fertility, organic matter promotes soil macro and microorganisms' activity. These soil organisms are beneficial in degrading crude organic compounds, mobilizing and remobilizing nitrogen and other nutrients, and play in symbiotic processes. The dynamic actions of these organisms affect soil porosity and permeability; two major physical characteristics that maintain soil vitality through gas and water exchange (Altieri *et al.,* 2015). In terms of minerals, organic matter is a nutrient pool, which through mineralization is released and available for absorption by plants. The organic matters retain on its surface adsorbed cations and anions. Its cation exchange capacity is very high: ~ 200-cmolc kg^{-1} against ~ 30-cmolc kg^{-1} for an illite-type clay. Thus, the organic matter content has a strong influence on the soil's capacity to retain and restore nutrients, protecting them from leaching (Dignan *et al.,* 2016).

Table 1. Success stories on the beneficial effects of crop-livestock integrated farming system in alleviating soil degradation and depletion

References	Location	Research goal	Key lessons learned
Ryschawy *et al.*, 2012	France	Identify pathways for improving soil self-sufficiency	Farming systems based on ICLFS lead to farm independence from external fertilizers
Duncan *et al.*, 2013	Kenya	Strengthening knowledge of ICLFS as a leading model for agricultural intensification in Africa	A mutual better utilization of benefits from ICLFS contributes to agriculture with high ecological value through sustainability of soil fertility.
Sulc and Franzluebbers, 2013	USA	Evaluate the potential of ICLFS in achieving soil stewardship	ICLFS offer opportunities for positive interactions with the soil, a strategy that allows to efficiently improve soil-plant relationships
Ezeaku *et al.*, 2015	Nigeria	This paper examines the imperatives of ICLFS for soil restoration	Crop rotation between cereals and legumes along with the use of manure improves soil biophysical properties for sustainable forage production
Patel *et al.*, 2015	India	Strengthen knowledge regarding need for crop-livestock integration	India has a large poultry and cattle population and extensive crop residues; strategies for re-using such components in crop and animal husbandry are an immutable core to sustainable agriculture
Mona *et al.*, 2018	Egypt	Evaluate ICLFS in alleviating agricultural production constraints.	Soil fertility decline is a major constraint to agricultural production in New Valley Region. ICLFS is an effective response to this issue and allows the improvement of soil fertility for sustainable agricultural production.
Zamukulu *et al.*, 2019	DRC	Assessing opportunities offered by ICLFS in highland areas of eastern DRC	Farms that adopt a ICLFS produce manure for soil restoration and feed their cattle with crop residues and crop residues serve as mulching to preserve soil from erosion and soil water loss.
Ahmed *et al.*, 2020	Egypt	This study compares the relative technical efficiency of ICLFS between the Upper and Delta regions of Egypt	The ICLFS has improved soil fertility, which led to the technical efficiency of farmers in both regions.
Dias *et al.*, 2020	Brazil	To appraise nutrient use efficiency in different agrosystems	An ICLFS combined with a forage production provided more efficient nutrient cycling compared to the pure maize cropping system

		based on maize and Brachiaria	
Alary *et al.*, 2020	Egypt	Assess how the crop-livestock integrated system affects efficiency of small-scale producers in western desert regions	Farms that rotate crops with fodder legumes and use manure as the mainstay of fertilization have higher agronomic efficiency in land use than productivist farms
Sulaiman *et al.*, 2020	Nigeria	Assess drivers of profit efficiency among rural communities in north-west Nigeria	Soil fertility improved by crop-livestock integrated system is the key factor that improved crop yield, resulting in high profit efficiency
Peterson *et al.*, 2020	Brazil	Contribute to soybean intensification through sustainable soil fertility management	This study demonstrates the suitability of the use of integrated systems for increasing soil organic matter stock for sustainable production of soybean-based forage
Rufino *et al.*, 2021	Mali	These authors discuss the role of ICLFS in Africa's soil stability, characterized by an important mineral leaching.	African agricultural policies need to effectively rely on crop-livestock integrated systems, which hold proven potential for sustainable soil management
Musara *et al.*, 2021	Zimbabwe	Assessing producers' perceptions on ICLFS as an effective soil management strategy	Farmers have a highly positive knowledge concerning the effectiveness of grains-livestock integrated system as a fundamental strategy to sustain soil fertility

Organic matter contributes to soil structuring. Some compounds produced by soil organisms, such as polysaccharides, act as glue between mineral particles, thus contributing to the aggregation of soil particles. Stabilized organic matter is colloidal material, which participates in the clay-humus complex due to its surface charge. The deep link between organic matter and clays also contributes to stable aggregates, and hence, to macroporosity, which is a positive structure for plant rooting function (Peterson *et al.*, 2020).

Liebig *et al.* (2017) indicated that the ICLFS over 12 years had been effective in enhancing soil nitrogen and phosphorus stocks and simultaneously had significantly reduced soil acidity. Similarly, experiments conducted by Denardin *et al.* (2020) aimed at assessing how integrated farming systems improve soil mineral status and rice yield. They indicated higher N, P and K accumulation in rice seedlings under integrated systems than under conventional systems. They also reported that rice yield was enhanced by more than 40% under integrated systems. Mineral recycling in integrated crop-livestock systems increased organic carbon, soil aggregate stability, soil microbial biomass, N and soil enzyme activities. A similar study by De Sant-Anna *et al.* (2016) showed higher levels of total nitrogen, total organic carbon, and water stability in integrated plots than in non-integrated ones.

Ecosystem processes in integrated crop-livestock systems provide significant active microbial diversity and improved soil structure and soil organic stock, which translates into increased biophysical protection against environmental shocks such as nutrient leaching and uncontrolled soil thermal fluctuations. In line with the foregoing, several studies including that by Denardin *et al.* (2020) have reported that upon integration of livestock into cropping, there was an improvement in total nitrogen content, organic carbon, soil microbial biomass and a decrease in soil resistance to root penetration due to an increase in the stable fraction of soil aggregates.

Therefore, the benefits of crop-livestock integration on sustainable soil fertility management are based on the synergistic force between the different systemic components, including animal manure, crop residues and the complexity of the trophic chain in pastures.

INTEGRATED CROP-LIVESTOCK SYSTEMS STRATEGY FOR CLIMATE CHANGE MITIGATION

Crop and livestock farming conducted under specialized models are blamed for contributing to global warming through methane and nitrous oxide emissions (Gorssi *et al.*, 2019). Methane, predominantly produced through enteric fermentation and manure storage, is one of the greenhouse gases that has 28-fold greater effect on global warming than carbon dioxide. Nitrous oxide, resulting from manure storage, is a molecule with 265 times the global warming potential of carbon dioxide (Stocker *et al.*, 2013).

Integrating crops with livestock or livestock with crops is a sustainable agriculture model based on dynamic interactions between animal and plant components to either alleviate their contribution to climate change or to support resilience to climate shocks (Table 2). The resilience of agrosystems is crucial to secure the well-being of agriculture under aggressive and uncertain climatic trends; it is based on principles that support adaptation and self-reliance in organizing and supporting substantial functions against stress indicators or local disturbances.

Table 2. Success stories on the beneficial effects of crop-livestock integrated farming systems to mitigate climate change.

References	Location	Research goal	Key lessons learned
Kabirizi *et al.*, 2014	Uganda	Assessing smallholder farmers’ strategies to mitigate climate change.	Farmers used ICLFS as core strategies to climate change mitigation
Ahmad and Ma, 2015	Pakistan	Provide a reference framework for developing agricultural systems suitable for climate change	Rural households' livelihoods are improved through their resilience to climate change, crop-livestock integration is the central component of this resilience.
Rigolot *et al.*, 2015	Burkina Faso	Identify farmers' resilience strategies to climate shocks in the Yatenga region	Households integrating crops with livestock have a higher resilience level than households in isolated farming systems

Thortnton and Herrero, 2015	Kenya	Assessing the potential of crop-livestock interactions as adaptation strategies to climate change	ICLFS are an effective strategy for managing climatic shocks through a risk re-assignment between components
Ghahraman and Moore, 2016	Australia	Examine the effectiveness of climate adaptation options among small-scale producers	ICLFS offer more potential to mitigate climate change compared to sole systems
Asante *et al.*, 2017	Ghana	Examine the determinants of smallholders' adaptation to climate change in Ghana.	ICLFS is a key factor explaining the resilience of producers to climate change
Da Conceição *et al.*, 2017	Brazil	Identify farming systems that enhance soil organic carbon stocks and reduce greenhouse gas emissions related to climate change	ICLFS strategies exhibited more potential for soil carbon storage with values similar to the quantity provided by Nature forest
Brewer and Gaudin, 2018	USA	Understanding the benefit of ICLFS in carbon sequestration	ICLFS impact soil carbon stock dynamics of croplands by altering biomass production, residual crop nutrient recycling, biological activity and food network complexity, soil structure, and physical protection of soil carbon
Chalise *et al.*, 2018	USA	To assess potential changes to water yield due to the introduction of different integrated plant-livestock based systems for a long-term period (31 years; 1980-2010).	Incorporating integrated cattle-maize or winter barley residue has a positive effect on the processes involved in soil water storage and transit (i.e., runoff volume, lateral flow and groundwater flow)
Bawa *et al.*, 2021	USA	Analyze the potential of long-term management of ICLFS on hydrological and climatic conditions.	ICLFS offer the potential to reduce surface runoff by improving soil hydrological conditions.

Several authors reported consistent results of integrated farming systems' resilience to weather hazards compared to specialized farming systems. For instance, Petterson *et al.*, (2020) indicated that integrated soybean-cattle systems showed greater resilience than the specialized system in response to rainfall anomalies in both historical and future weather simulations. Indeed, with integrated crop-livestock systems, there is efficient management of organic matter, which offers the possibility of increasing the soil holding capacity. Humid organic matter, as opposed to clay, has a strong capacity to retain water, and therefore, has a hydrophilic property that allows absorption and improvement of water use efficiency for crops. To this benefit, it is necessary to mention that through its cohesion and aggregation properties, organic matter also acts on soil porosity, thereby reducing soil infiltration capacity (Osborne *et al.*, 2014).

The promotion of diversity and integration within agroecosystems has been defined for several decades as an advanced model of strategy development that strengthens resilience through the continuation of ecosystem processes and cumulative effects along environmental chains (Basche *et al.*, 2016). Furthermore, by providing a sound and sustainable strategy for soil fertility management through the introduction of fodder legumes in pastures, crop residues valorization and manure production, ICLFS provide approved alternatives to synthetic fertilizers which are responsible for greenhouse gases.

It is noteworthy that grasslands and pastures integrated with agriculture occupy 3460 million ha worldwide; hence, the restoration and effective management of these ecosystems is an important carbon sequestration site. For instance, an efficient livestock system integrated with agriculture may improve carbon sequestration from 0.11 to 3.04 Mg C/ha/year with an average of 0.54 Mg C/ha/year, providing significant benefits for global warming management (Stavi and Lal, 2015).

Integrated plant-animal systems, through regulating and catalyzing mechanisms involved in specific biophysical processes such as nutrient recycling, productivity enhancement, economic risk alleviation, and diversification of livelihood options, provide a crosscutting model for climate risk management. Descheemaeker *et al.* (2016) pointed out that, the design of climate shock mitigation strategies must focus on risk management opportunities through diversification and sustainable intensification. For this purpose, ICLFS generally integrate such an approach. These authors argue that risk management aims to reduce the variance of an outcome (e.g., crop yield), whereas intensification is specifically designed to improve the average outcome. Diversification, however, is likely to induce a modification of both variance and average.

INTEGRATED CROP-AQUACULTURE FARMING SYSTEMS (ICAFS)

Basis and principle. ICAFS is an effective tool for the development of sustainable agricultural policies based on food self-sufficiency (Figure 2). Households involved in this scheme have an opportunity to produce fish and plants simultaneously, two major edible resources in the food chain, but cost-effectively. This production is based on low use of production factors and sustainable environmental management (Bosma *et al.*, 2014).

The ICAFS is based upon the idea that “nothing is lost, nothing is created, everything is transformed”. The sub-products of crop production are considered inputs for fish production and vice versa. Such a system is based on exploiting the synergistic effects of the two components for a rational, efficient and sustainable use of the involved systemic resources.

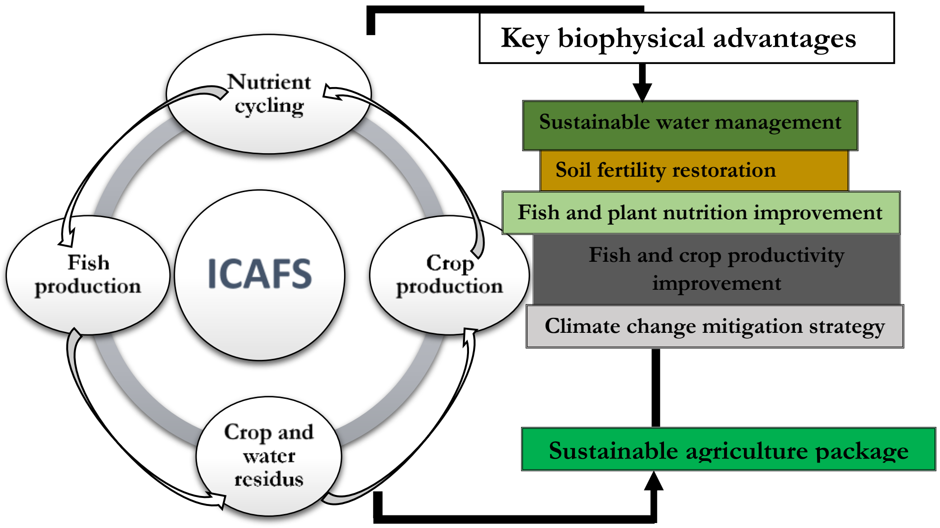

Figure 2. Framework of Integrated crop-aquaculture farming system and key biophysical advantages

However, in most cases, the main component is the fish, which exploits the plant by-products directly or indirectly for food. In addition, plant production integrated with fish takes advantage of the recycling system of aquaculture by-products, such as water and other solid components, to support the soil fertilization system. The above synergy is an approved approach to sustainable use of production factors, allowing intensive use of the available area to maximize both crop and fish production, for example (Moore *et al.*, 2020).

INTEGRATED CROP-AQUACULTURE FARMING STRATEGY FOR SUSTAINABLE WATER MANAGEMENT, SOIL FERTILITY, CROP AND FISH PRODUCTIVITY

Overall, ICAFS have been demonstrated to improve water cycling; sustainable management of weeds and insect pests that fish incorporate into their diets; and fish excrement ensures nutrient availability and improves soil nutrient mineralization (Bhavsar *et al.*, 2016).

In the context of restricted access to production factors, such as irrigation water and fertilizers, the ICAFS offers to small-scale producers the possibility of access to irrigation water, which constitutes an optimal strategy for water utilization (table 3). At the same time, this water is enriched in minerals, which may be filtered through the soil and added to the soil's mineral reserve (Baills *et al.*, 2019). Many studies, conducted under various integrated crop-aquaculture systems, indicated the benefit of integrated systems over specialized ones. For instance, these studies demonstrated the benefit of the fish-vegetable (Da *et al.*, 2020); fish-sesame (Soliman *et al.*, 2020); aquaculture-sugar beet (El-Kady and Helmy, 2020); and fish-rice farms (Ramachandra *et al.*, 2019). Furthermore, Van Huong *et al.*, (2019) argued that rice produced under pure cropping system involves high fuel consumption due to excessive use of synthetic inputs and mechanization, which results in high environmental impact and unsustainable productivity. To overcome these challenges, these authors suggested that integrating rice production with aquaculture could provide an opportunity to develop a rice production system with low negative environmental impact.

Table 3. Success stories on the beneficial effects of crop-aquaculture integrated farming for sustainable water management, soil fertility, and crop and fish productivity.

References	Location	Research goal	Key lessons learned
Gupta *et al.*, 2015	India	Explore the multidimensional nature of agro-ecological systems in environmental resilience	ICAFS, one of the agro-ecological farming systems that offer opportunities for water and soil sustainable management among smallholders.
Islam *et al.*, 2015	Bangladesh	Identify ecosystem services provided under ICAFS	Among the diversity of ecosystem services provided under the integrative strategy, soil and water use efficiency are the emphasis
Bhavsar *et al.*, 2016	India	Assessing the potential of ICAFS to prevent environmental pollution	An ICAFS prevents environmental pollution by reusing the waste products of both components in the production system.
Efole *et al.*, 2017	Cameroon	Understand the strategies used by fish farmers and environmental constraints	Integration of crop to aquaculture allows improving biophysical water properties for fish production
Mafwila *et al.*, 2019	DRC	Elucidate environmental benefits of an integrated crop-aquaculture system	Integrated systems are an effective strategy for efficient management of production factors, including water and soil.
Van Huong *et al.*, 2019	Vietnam	Analyze the contribution of integrated crop-aquaculture to food security	There was a significant role of integrated crop-aquaculture systems in achieving food security through efficient water and soil management
Kabir *et al.*, 2020	Bangladesh	Analyze farmers' perception and environmental risk management in rice-shrimp based farming systems	Integrating rice cultivation into ponds settled by shrimp reduces the use of agrochemicals
Respikius *et al.*, 2020	Tanzania	Exploring the potentials, challenges and opportunities for promoting ICAFS	Crop-aquaculture integrated system offers the potential for sustainable water management
Chakrabarti and Banerjee, 2021	West Bengal	Examining the potential of ICAFS as a sustainable development strategy	This system involves recycling waste or by-products from one agricultural system as inputs to another compatible system.

Mulokozi *et al.*, 2021	Tanzania	Explore the existing potential of ICAFS	The system allows an improvement of water and soil biophysical properties to the advantage of fish and plant productions
Zohra *et al.*, 2021	Egypt	Assess the effect of irrigation water from aquaculture on the agronomic performance of cultivated species	Aquaculture water improves crop yields and the system allows for water use efficiency

In the case of the rice-fish integrated system that is very popular due to rice agronomic particularity, an integrated system is interesting for managing weeds in an integrated approach. Indeed, in the fish population, there are some types of fish, which feed on aquatic fauna and flora that are harmful to plants. These predatory organisms constitute an opportunity to establish a biological strategy to control plant pests. For instance, it has been proven that common carp constitute a formidable predator, which reduces the snail population, whose ravages on plants are indisputable (Aravindakshan *et al.,* 2019).

Thus, the involvement of fish, a human food resource, as a component of biological control in plant production would not only reduce the quantity of synthetic products used in chemical control but also the strategy is effective in improving the productivity of agricultural assets (Ahmed and Turchini, 2021). In addition, some species of ichthyologic communities such as common carp, Nile tilapia, and silver barb have been proven to decrease filamentous algae and other floating and submerged weed species. Reducing weed biomass under such conditions is straightforward, inexpensive, fast and without significant ecological consequences (Babiola *et al.,* 2019).

From the foregoing, it is evident that ICAFS is a viable option to sustainably increase water availability, soil fertility and agricultural asset productivity. It is important to have practical knowledge of local fish farming conditions that will need to consider: (i) availability, flow rate and quality of water from the source of supply; (ii) the composition of the pond for biodiversity, biophysical interactions and fish feeding must be also included; (iii) local possibilities offered by the environment for water and sediment reuse in agriculture; and especially (iv) types of plant species to integrate with aquaculture. The interest in launching this scheme will depend on the technical opportunities offered by the local environment and the technical ability of the producer (Edwards, 2015; Abdelraouf and Ragab, 2017).

INTEGRATED CROP-AQUACULTURE FARMING AS A STRATEGY FOR CLIMATE CHANGE MITIGATION

Integrated farming systems remain a credible strategy for operationalizing farming systems that allow for water use efficiency in the context of scarcity and limitation. Water as an ecological factor substantially related to agricultural production, therefore, requires rational and sustainable use (Table 4). It is important to increase water use efficiency by increasing the quantity of agricultural commodities produced per unit of water consumed (Berg *et al.,* 2012).

Table 4. Success stories on the beneficial effects of crop-aquaculture integrated farming systems for climate change resilience and mitigation

References	Location	Research goal	Key lessons learned
Kumar *et al.*, 2016	India	Evaluating various scenarios for water use efficiency under the conditions of low water resources due to climate change	Reusing water from fish production in agriculture is a sustainable water management strategy in a climate change context.
Zougmoré *et al.*, 2016	Mali	Identify high-level strategies to mitigate climate change effects in agricultural systems	The ICAFS is ranked as one of the high impact strategy to climate change alleviating
Cánovas-Molina and García-Frapolli, 2018	Mexico	Determine a strategy to reduce environmental pollution due to industrial aquaculture	Integration of crop into aquaculture provides opportunities to reduce environmental risks around industrial aquaculture
Baills *et al.*, 2019	France	Assessing opportunities for adapting coastal lands to climate change	Besides irrigation, integration of crops and aquaculture is a major approach for coastal land mitigation to climate change
Afokpe *et al.*, 2022	Benin	Examine advances in climate change adaptation and mitigation actions in sub-Saharan Africa.	The ICAFS is pointed as one of the substantial strategies to climate change mitigation in sub-Saharan Africa.
Fan *et al.*, 2021	China	Determine the form of sustainable water use management under the climate change context	ICAFS offers more opportunities to build farmers' capacities toward climate adaptation
Nong *et al.*, 2021	Vietnam	Determine coastal agricultural land use strategies in response to climate change	ICAFS is a key mechanism for adapting coastal lands to climate change
Varyvoda and Taren, 2022	USA	Identify agricultural systems delivering ecosystem services in response to climate change	Agriculture combined with aquaculture is an effective strategy for thermal regulation.

The ICAFS is likely to contribute to greenhouse gas reductions compared to systems that support the specialized production of both components (Paramesh *et al.*, 2021). The integrated system is based on a circular approach of input use and some production factors such as water, which allows reducing greenhouse gases avoiding a large use of chemicals in plant fertilization and fish feeding. In a climate change context where water pressure is significant, the integrated crop-fish production system offers opportunities for efficient water use between the two key agricultural sectors. A situation arises where plants and fish are produced using practically the same water (Hanjra *et al.*, 2015).

Greenhouse gas emissions responsible for climate change are supported at significant proportions by the specialized production of rice, fruit crops, vegetables and other types of plants and yet, the integration of aquaculture in the agricultural systems based on these crops is likely to reduce the use of synthetic products in their productions. Moreover, the management of crop residues, in specialized cultivation is also an important source of greenhouse gas emissions. As an example, in extensive rice cultivation, during the microbial degradation of rice straw in a flooded system, a significant production of methane is occurring (Yuen *et al.*, 2021).

However, under integrated rice-aquaculture systems, the activities of different metabolisms of the carp fish, such as feeding and respiration, allow disturbance of the soil's upper layers, and may therefore, compromise the methane synthesis process. Some authors even suspected that oxygen might be incorporated into soil through fish feeding activities, which would also mitigate methanogenic processes and promote carbon storage through sediment accumulation. Nevertheless, Varyvoda and Taren (2022) indicated that more evidence is needed to demonstrate the positive contribution of fish to control greenhouse gas emissions.

Several other authors, including Feng *et al.* (2016), Moore *et al.* (2020) and Naiel *et al.* (2021), believe that integrated plant-fish systems will minimize the effects of climate shocks and secure producers' incomes by promoting income diversity, water use efficiency and nutrient recycling.

CONCLUSIONS AND PERSPECTIVES

Integrated crop-livestock and crop-aquaculture farming systems are likely to provide strategies for increasing environmental resilience among smallholder farmers in the context of environmental dynamics which involve several risk factors. Environmental resilience is expected as the producer's ability to balance environmental supply with the requirements of key agricultural production components, including plants, animals and fish, about biophysical environmental conditions. Mainly in the face of the problem of soil fertility degradation, climate change and efficient management of agricultural water, these systems are alternatives to support the efforts of producers despite the uncertainties around production factors.

However, most approaches developed to understand the environmental resilience of integrated crop-livestock and crop-aquaculture systems are essentially analytical, and experimentally based on the development of technical standards. In contrast, analysis of the rationale and expectations of stakeholders has long been overlooked when pointing directly to the advantages of integrated systems. Based on a well-defined typology, the systemic analysis approach monitored directly during several production cycles at the smallholder scale is relevant for addressing research questions simultaneously under the biotechnical, socio-economic and organizational standpoints.

This approach needs to consider the dynamic relationships of each component by seeking articulations among practices, guidelines and various interactions. The general approach is based on action research considering the farm in its specific philosophy and context. As ICLFS and ICAFS exist in many rural environments, it is therefore important to further mobilize the research-action segment to model their structure, functioning and management, but also to mobilize indicators usable to support understanding of resilience offered at the individual and community scales. The methodology suggested fits effectively within the research for development (R4D) framework, the understanding of integrated crop-livestock and crop-aquaculture farming systems through research with producers and for producers.

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STATEMENT OF NO-CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in this paper.

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