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Original Research Paper

Assessment of Ecosystem Services Delivered by Mixed Crop-Livestock Farming Systems

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Abstract: Mixed crop-livestock farming systems are becoming a viable farming paradigm that can solve the current agricultural problems of food security, resource scarcity, environmental degradation and climate change. Traditional agriculture can use intensive inputs, leading to reduced soil health, biodiversity, and the effective use of resources, and a rise in greenhouse gas emissions. The aim of this study is to provide a broad-based evaluation of the outputs of mixed crop livestock farming systems and to develop a framework for integrated ecosystem service assessment to facilitate decisions for sustainable agriculture. The proposed methodology integrates ecological, environmental, economic and social sustainability parameters along with contemporary assessment tools such as Geographic Information Systems (GIS), Remote Sensing, Internet of Things (IoT) based monitoring, Multi-Criteria Decision Analysis (MCDA) and Artificial Intelligence (AI) for comprehensive assessment of the ecosystems. Comparative analysis shows that the mixed crop-livestock farming systems outperform conventional systems in terms of soil fertility (high vs. moderate), nutrient recycling (92% vs. 48%), water-use efficiency (88% vs. 65%), biodiversity index (0.84 vs. 0.52), carbon sequestration (4.5 vs. 1.8 t/ha/year), and benefit-cost ratio (2.18 vs. 1.55). In addition, the integrated framework maximizes the efficiency of resource use and decreases the reliance on outside resources, increases climate resilience, and improves farm profitability by implementing a circular approach to resource utilization. The results show that mixed farming of livestock and crops is a sustainable pathway of agricultural intensification, ecosystem conservation and long-term agricultural development which can support the formulation of evidence-based policy and precision agricultural management.

Keywords: Mixed crop-livestock farming, ecosystem services, sustainable agriculture, biodiversity conservation, nutrient cycling, carbon sequestration, ecosystem assessment, precision agriculture, GIS, remote sensing, MCDA, artificial intelligence.

I. Introduction

Agriculture is critical for food security, rural economies and rural living standards across the globe. Population growth, higher food demand, global climate change and natural resource degradation, however, are putting unprecedented stress on global agriculture. In the past, agriculture has been practiced in a traditional way and prioritized high inputs such as monoculture and intensive agriculture for livestock, which has had a positive impact on food production but also has led to biodiversity loss, greenhouse gas emissions, depletion of natural resources, water pollution, and soil degradation. Such environmental problems have given rise to serious concerns for the sustainability of modern agriculture in the long-term. This has led to a surge of interest in farming systems that can meet multiple objectives – both high levels of agricultural production and the maintenance of ecosystem health and environmental sustainability – that are increasingly being sought after globally [1] [3].

Mixed crop-livestock agriculture systems are one of the most promising strategies towards sustainable

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agriculture. These systems include the integration of crops and livestock in a single farm operation, and the proper use of available resources by using ecological interaction. Crop residues are used for animal feed and animal manure is used for organic fertilizers, which helps to improve the fertility of the soil and decrease the reliance on chemical fertilizers. Livestock grazing can aid in weed control and nutrient redistribution, while diversified crop systems can enhance soil structure, water holding capacity and protect against pests and diseases. This integrated resource management is like an effective multipurpose management which increases productivity and reduces the impact on the environment as well as the resilience of the farming system to climate variability and changes. In recent years, many studies have shown that integrated farming systems are more energy efficient, have lower greenhouse gas emissions, better nutrient cycles and more sustainable in terms of livelihoods than conventional farming systems [4, 3, 1].

This notion of ecosystem services is very useful to grasp the various environmental, economic and social services produced by mixed crop-livestock systems. Ecosystem services are the benefits that people receive from natural ecosystems, and are broadly divided into four categories: provisioning, regulating, supporting and cultural services. Provisioning services involve the production of food, milk, meat, fodder and fiber. Carbon sequestration, regulation of climate, regulation of nutrients, control of erosion and water purification are among the regulating services. Supporting services are related to soil formation, nutrient cycling, biodiversity, pollination, etc. and cultural services are related to traditional farming methods, rural heritage, recreational value, etc. and improvement of community well-being. These ecosystem services can be synergised due to the integrated crop-livestock production system, which can enhance agricultural productivity and environmental sustainability. Integrated agricultural systems have also been shown to have a vital role in providing ecosystem services in terms of environmental balance and long-term sustainability by means of emergy-based ecosystem service valuation [5, 6].

Although mixed farming systems are known to have many benefits, they are difficult to measure the ecosystem services they provide. Past studies have largely concentrated on specific ecosystem services including soil fertility enhancement, carbon sequestration, biodiversity conservation and economic value. These studies offer useful information, but tend to not consider the total ecological, environmental, economic and social returns from mixed crop-livestock systems. In addition, the assessment of ecosystem services is very complex and location-specific, as they are influenced by many factors such as the climate, soil condition, farming practices, landscape and management. Different geographical areas and agricultural systems may also make it difficult to compare research findings due to the lack of common indicators and common evaluation methods [3, 5, 6].

There are also a number of limitations with current methods of assessment that hinder their effectiveness for supporting sustainable agricultural decision making. Most traditional assessment methods use individual environmental parameters and fail to consider the interdependencies between soil, crops, livestock, biodiversity and climate. The ecological values of non-market ecosystem services, like habitat protection, nutrient cycling and pollination, are underestimated by many economic valuation methods. Furthermore, traditional assessment methods tend to rely on regular field visits and overlooks seasonal variations and long-term ecological shifts. The use of high-end technologies like remote sensing, Geographic Information Systems (GIS), Internet of Things (IoT)-based environmental monitoring, artificial intelligence and machine learning is also limited, which further reduces the power to do continuous, accurate, and comprehensive estimation of ecosystem services. Furthermore, most of the current frameworks are lacking in the ability to have holistic decision support processes that include environmental, economic and social sustainability indicators in the process [2, 4, 6].

These are the limitations overcome by recent advances in precision agriculture, environmental monitoring technologies, remote sensing, geospatial analysis, AI and explainable AI. Sophisticated sensing systems allow for monitoring of soil condition, vegetation growth, livestock performance, water availability, and climatic conditions on a continuous basis and intelligent analysis models allow for precise soil condition assessment and prediction of long-term sustainability outcomes that measure ecosystem services. EAI is another step towards transparency and reliability in agricultural decision-making, allowing stakeholders to understand the analysis results and leverage their strategies for better resource management [2]. Combining these technologies into ecosystem service assessment tools can greatly enhance decision making and resource allocation, environment protection and adaptive farm management [2, 4].

The goal of this study in this context is to capture a comprehensive indicator of the ecosystem services provided by mixed crop-livestock farming systems, combining ecological, environmental, economic and technological aspects. The study summarizes the big ecosystem services of integrated farming systems, surveys the currently available indicators ofES assessment and evaluation methods, summarizes the challenges of available methods and suggests an integrated framework ofES assessment including nine indicators and a seven-step method to assist sustainable agricultural planning and management. The suggested framework highlights the importance of considering nutrient cycling, biodiversity conservation, soil health, water resource management, carbon sequestration, precision agriculture technologies, and decision-support systems in order to comprehensively assess sustainability.

This paper makes the following four main contributions. It first offers an extensive survey of the ecosystem services that mixed crop-livestock production systems provide and why they are important to sustainable agriculture. Second, it reviews and discusses the current approaches to assessing ecosystem services and pinpoints areas for further research and methodological limitations. Third, it suggests a framework for integrated assessment that integrates ecological indicators, environmental monitoring technologies and sustainability evaluation techniques to enhance the evaluation of ecosystems services. Finally, the paper compares the benefits of mixed crop/livestock farming systems versus conventional farming methods from an ecological, economic and environmental perspective. Based on the results of this study, evidence-informed approaches and solutions can be developed that can support researchers, policy makers, agricultural planners and farmers in creating resilient, productive and environmentally friendly farming systems that can contribute to global food security and climate resilience targets of the future [1]–[6].

II. Literature Review

Mixed crop-livestock farming systems have garnered significant attention as truly sustainable agricultural systems that combine crop and livestock production to optimise resource use with reduced impacts on the environment. These two farming components help to facilitate efficient nutrient cycling, enable better soil fertility, biodiversity and resilience of farms to climate variability. Recent studies suggest that these systems offer several ecosystem services such as provision, regulating, supporting and cultural, and can support both agricultural production and environmental sustainability [8] [9]. The use of advanced sustainability assessment (SA) approaches has been used in several studies to investigate the ecological and economic benefits of IFS. Emergy analysis is one of the most popular methods for assessing the ecological performance since it takes into account both natural resources and human resource inputs. Emery analysis has been used for sustainable crop production assessment and it has been shown that the measures of sustainable crop production based on ecological indicators give a more comprehensive assessment than the standard productivity indicators. The studies mentioned indicated that integrated farming systems have a tremendous positive effect on resource-use efficiency, decrease environmental degradation and contribute to long-term ecological conservation.

Consultation with researchers also includes an assessment of co-benefits, which includes multiple environmental, economic and energy indicators for the integration of livestock and cropland systems. Integrated crop-livestock systems have been demonstrated to decrease the carbon footprints of such operations due to efficient nutrient recycling, decrease reliance on synthetic fertilizers and better farm profitability. Crops and livestock working together helps maximize resource use and minimize greenhouse gas emissions and environmental degradation. The results of such efforts underscore the need to use multi-objective assessment approaches that consider multiple ecosystem services at once instead of only sustainability indicators [7]. The development of ecosystem service indicators (identification and quantification) is another research area of importance. A number of ecological indicators have been suggested to assess soil health, soil biodiversity protection, nutrient cycling, carbon sequestration, water regulation and agricultural productivity in livestock farming. These indicators offer a scientific framework to quantify the performance of the ecosystems and help in agricultural planning based on evidence. Researchers have noted, however, that there is a lack of integration of many of those indicators and they need additional standardization to allow for comparable assessments of the various farming systems and geographic locations. [8]

Meta-analyses studies carried out on a large scale have also reinforced the evidence for mixed systems of crop-livestock production. Several experimental studies have shown that integrated farming systems better preserve biodiversity, increase nitrogen-use efficiency, build up soil organic carbon stocks, and perform better in environmental aspects compared to specialized farming systems, through comparative evaluation. Moreover, these systems have also demonstrated to be more economically resilient as they offer more farm income diversification and mitigate the production risk arising from market fluctuations and climate variability. However, there are also certain differences in the economic and environmental performance of the integrated farming systems in terms of regional context, farm management practices and policy support, which means it is necessary to have assessment frameworks that are location specific [9]. A second research focus would be to assess the environmental advantages and/or risks of integrated crop-livestock systems. These systems are able to significantly benefit ecosystem services due to their ability to recycle waste, improve soil quality, and better utilise resources; however, improper manure management and nutrient loading can result in environmental hazards like water pollution and nutrient imbalance. Researchers therefore have suggested the development of integrated environmental monitoring systems (IEMS) that not only monitor the health of ecosystems on an ongoing basis, but also offer a way to manage agricultural production and environmental protection. This assessment type is crucial for achieving the delivery of ecosystem services while reducing the adverse effects of the activities in the ecosystem [10].

While all this progress has been made, there are still several areas where research is needed. The majority of current research focuses on individual aspects of sustainability, e.g., carbon emissions, emergy analysis, conservation of biodiversity, economic performance or ecosystem services indicators, amongst others. There are only a few studies that have incorporated these various assessment methods in one consolidated framework that can assess provisioning, regulating, supporting and cultural ESS. Moreover, the application of new technologies like remote sensing, Geographic Information Systems (GIS), Internet of Things (IoT)-based environmental monitoring and artificial intelligence and decision support systems in assessing ecosystems services is still limited. Thus, a need of developing an all-encompassing ecosystem services assessment framework is increasing, involving ‘ecological indicators', ‘environmental monitoring technologies', ‘economics evaluation', and ‘intelligent decision-support tools' for sustainable management of mixed crop-livestock farming systems and for evidence-based agricultural policy development [6]–[10].

Methodology	**Key Findings**	**Research Gap**
Global meta-analysis of 700 studies from 270 publications, J.-J. Minviel and P. Veysset (2026)	Mixed crop-livestock systems significantly improve biodiversity, soil organic carbon, nitrogen-use efficiency, and reduce greenhouse gas emissions compared to specialized farming systems.	Limited validation using real-world commercial farms; greater emphasis on integrated field-scale assessment is needed.
Comprehensive review of global case studies, Y. Lou and K. Mo (2025)	Demonstrated improved resource utilization, crop productivity, and ecosystem services while highlighting emerging environmental risks associated with manure management and pollutants.	Lack of standardized environmental risk assessment models integrated with ecosystem service evaluation.
Ecosystem service evaluation considering provisioning, regulating, supporting, and cultural services, S. Kumar, M. A. Ansari, P. C. Ghasal, J. Choudhary *et al.* (2025)	Integrated farming systems enhance biodiversity, nutrient cycling, carbon sequestration, soil fertility, and livelihood resilience.	Quantitative evaluation frameworks and standardized performance indicators require further development.
Comprehensive survey of over 200 AI studies, U. Nawaz, M. Z. Zaheer, F. S. Khan, H. Cholakkal, S. Khan, and R. M. Anwer (2025)	AI, deep learning, and vision-language models improve crop monitoring, livestock health management, and precision agriculture, enabling data-driven farm management.	Limited application of multimodal AI for integrated ecosystem service assessment in mixed farming systems.
System dynamics and multidisciplinary sensitivity analysis, J. Ibáñez, J. Martínez-Valderrama, J. F. Lavado Contador	Climate change and land-use practices strongly influence ecosystem services, farm profitability, and soil conservation, emphasizing the need for integrated policy frameworks.	The framework does not explicitly evaluate crop-livestock ecosystem service interactions or biodiversity indicators.

Table 1. Summary of Existing Methodologies

Table 1 provides a list of recent studies on the provisioning of ecosystem services related to mixed crop-livestock production systems, along with research objectives, methods, key results and gaps identified. The literature reviewed shows that integrated farming systems are effective in the integration of crop and livestock enterprises to enhance the resource-use efficiency, biodiversity conservation, soil fertility, carbon sequestration and overall farm sustainability. In recent years, there has been an increased focus on the ability of emergy analysis, ecosystem service valuation, precision agriculture and artificial intelligence in assisting in sustainable agricultural management. The review shows, however, that the bulk of current studies are restricted to specific ecosystem services or sustainability indicators with only a few studies providing a comprehensive assessment framework. These restrictions highlight the need for an integrated-ecosystem service evaluation model which integrates ecological, environmental, economic and technological factors to facilitate and guide the decision making process towards sustainable agricultural use in the long term.

III. Ecosystem Services in Mixed Crop-Livestock Farming Systems

Ecosystems services are the benefits that people benefit from natural ecosystems through ecological processes and interactions. In agricultural environments, these services are responsible for food production, environment conservation, climate control, and rural livelihoods. Mixed farming systems (crops and livestock) are especially efficient in providing several ecosystem services, since the crops and animals are integrated in a single system. Ecological synergies between crops, livestock, soil and water and biodiversity yield positive outcomes that lead to better use of resources and lower environmental degradation. According to the Millennium Ecosystem Assessment there are 4 ecosystem services which are provisioning, regulating, supporting and cultural services. Provisioning services are those that are material such as food, feed, fiber and fuel. Regulating services help maintain environmental quality by means of carbon sequestration, climate regulation, soil conservation and water purification. Services supporting agriculture enable nutrient cycling, soil formation, pollination and biodiversity conservation to sustain agricultural productivity. Cultural Services benefit the rural heritage, traditional knowledge, recreation and community health. All these services combine for sustainable agricultural development, where economic productivity is balanced with ecological integrity.

The most apparent products of mixed crop-livestock farming systems are provisioning services. They yield crops such as cereals, vegetables, fruits, forage crops, milk, beef, poultry, eggs, wool and other livestock products, thus improving food and nutrition security. Crop residue after harvestings can also be used as feed for livestock, which helps to reduce the need for commercial feeds and enhance farm efficiency. Similarly, livestock products provide another stream of income for farmers, lessening the impact of crop failure on farm profitability. Mixed farming systems also play a role in fiber production, such as cotton, flax, and wool and leather production. Further, the agricultural residues and manure of livestock can also be utilized for generating bio gas for rural households for renewable bio energy production which helps in decreasing dependence on fossil fuel. Adopting these several production activities raises the efficiency of using production resources, enhances farm profitability and boosts the resilience of livelihoods.

Ecosystem services need to be regulated to ensure the stability of the environment and a lower ecological footprint of agricultural production. A significant benefit of mixed farming systems is that livestock manure is a source of nutrients that are easily recycled back into the soil, thereby increasing soil microbial activity, soil structure and soil organic matter. Better soil fertility leads to better crop production and a decrease in the use of artificial fertilizers. Integrated farming systems also help to improve water regulation through an increase in the infiltration of water into the soil, decrease in runoff and increase in groundwater recharge. Maintenance of vegetative cover and diversification of cropping systems help control soil erosion and water quality by controlling nutrient loss. In addition, mixed farming plays a major role in climate change mitigation via carbon sequestration in soils, pasture lands, agro-forestry and perennial vegetation. Rational use of nutrients and reduction of the use of chemical fertilizers result in better environmental sustainability and reduction of greenhouse gas emissions.

Ecosystem services support allows ecological processes that are critical for future agricultural production. Nutrient cycling is one of the most important supporting services in mixed farming systems as the continuous recycling within the farming system of N, P, K and organic C, through crop residues and livestock manure occurs in the system. This is a natural nutrient cycle that helps to minimize waste generation and enhance soil quality. Insects and other beneficial organisms are involved in pollination which directly contributes to the production of crop and to fruit quality. A wide range of plant species and flowering plants, agroforestry and hedgerows provides good habitat for pollinators and beneficial insects. Mixed farming systems also favour the conservation of biodiversity through different species of plants, livestock breeds, microorganisms, birds and wildlife. A diversified biodiversity contributes to ecosystem stability, resistance to pests and diseases and climate variability. Supporting services in turn reinforce ecological sustainability in IFS and agricultural productivity in long-term perspective.

The mixed crop-livestock farming systems have many cultural and socio-economic advantages apart from the production. These systems are used to conserve traditional farming knowledge, indigenous livestock breeds and locally adapted cultivated varieties, which are the result of generations of evolution. Routine practices are helping to conserve cultural heritage and sustainable management of resources. Integrated farming systems produce multiple income-generating streams in the agricultural sector, such as in crop production, livestock production, production of organic fertilizers and production of renewable energy and thus are economically interesting. Diversifying farm income helps farmers to minimize their risk from market and climatic variability. In addition, mixed farming generates jobs in the cultivation of crops, animal rearing, processing, transportation and value adding agricultural activities. Sustainable farming methods also contribute to the resilience of rural communities by promoting food security, combating poverty, and boosting their overall well-being. Thus, mixed crop-livestock farming is important for sustainable rural development, as their socio-economic contributions.

IV. Assessment Indicators and Evaluation Methodologies

Assessing the health, productivity and sustainability of mixed crop-livestock farming systems is essential and requires the use of ecological indicators. These indicators measure ecosystem functions and give tangible proof of ecosystem performance. Soil organic carbon, soil fertility, microbial biomass, biodiversity indices, vegetation cover, crop productivity, livestock productivity, nutrient-use efficiency and habitat quality are some common ecological indicators. These indicators can be used to determine the impacts of various agricultural management practices on ecosystem health.

The diversity of microbes, abundance of pollinators and earthworms are becoming more common yardstick for assessing ecological stability and ecosystem resilience. Tracking these indicators over time can help to identify trends and patterns in the sustainability of integrated farming systems, and inform adaptive management practices.

Environmental assessment is primarily concerned with the assessment of the environmental consequences of agricultural operations and the climate. A carbon footprint analysis is used to assess the greenhouse gas (GHG) emissions from crop cultivation, livestock farming, fertiliser application and energy use. Water footprint analysis considers water use and efficiency in irrigation and nutrient balance assessment is used for the measurement of the losses of nitrogen and phosphorus to the environment. Other environmental indicators are soil erosion, land-use efficiency, biodiversity conservation indices, renewable energy use, waste recycling efficiency and ecological footprint. Climate resilience indicators like drought tolerance, water-use efficiency and adaptive capacity also help to assess the climate resilience of mixed farming systems. These metrics are used together to give an overall picture of the environmental sustainability.

Economic sustainability is used to assess the economic efficiency and sustainability of integrated farming systems. Major farm indicators include net return, benefit-cost ratio, production costs, return on investment, labour productivity, diversification of markets and farm income. Resource-use efficiency indicators measure the production of economic value from inputs in land, water, labour and energy. They quantify social sustainability indicators, such as rural economy development, employment creation, food security, nutrition diversity, gender inclusion, farmer education and community well-being. These other indicators assess resistance to economic shocks, sustainable farming technologies and impact on local economic development. Economic and social indicators complements productivity indicators to paint a picture of agricultural sustainability in its entirety.

Technology has advanced greatly over the past few years to greatly enhance the assessment of the ecosystem services, using remote sensing, GIS and precision agriculture technology. Satellite images and unmanned aerial vehicles (UAVs) yield high resolution data on vegetation health, crop growth, soil moisture, land use change and biodiversity patterns across far greater geographical areas. GIS can be used to perform spatial analysis of ecosystem services, when environmental data, climate data, topographic data and agricultural data are all combined. Soil moisture sensors, temperature sensors, nutrient sensors, livestock movement sensors, weather sensors and water quality sensors are continuously monitoring soil moisture, temperature, nutrients, livestock movement, weather and water quality in real-time. These vast amounts of data are then processed by AI and machine learning models to forecast crop growth, forecast environmental hazards, and streamline farm management decisions. These digital technologies greatly enhance the precision, scalability and efficiency of assessments of ecosystem services.

Multiple ecological, economic, environmental and social criteria may be used in the assessment of an ecosystem service, which can be difficult to consider simultaneously. Multi-Criteria Decision Analysis (MCDA) offers a structured approach that combines the use of various indicators in a comprehensive decision-making process. There are several techniques that are widely applied for sustainability assessment, such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment

Evaluation (PROMETHEE) and fuzzy decision models. Ecosystem service valuation models integrate ecological indicators with economic valuation techniques like emergy analysis, life cycle assessment (LCA), cost benefit analysis, contingent valuation, and ecosystem accounting. These methods measure the ecosystem services as well as the market ecosystem services, which allows the evaluation of various practices and make an informed decision for sustainable agriculture. The use of MCDA is enhanced by the application of digital technologies and ecosystem valuation models, which can help in the development of evidence-based policy formulation and contribute to the shift towards sustainable, resilient mixed crop-livestock systems in an environment of ecosystem services.

V. Ecosystem Service Performance Analysis

Soil health is fundamental to sustainable agriculture and ecosystem health. In addition, mixed cropping systems with livestock offer potential to enhance soil quality through their ability to stimulate natural nutrient cycling and accumulation of soil organic matter. Together, crop residues, livestock manure and biological decomposition replenish the vital nutrients like nitrogen, phosphorus and potassium, thereby minimizing the need for synthetic fertilizers. As organic materials are continually added to the soil, it will become more structured, more diverse with respect to microbes, hold more water and be more resistant to erosion. In addition, a diversified crop rotation and integrated grazing increases biological activity, thus promoting nutrient availability and long-term soil fertility. In a manner of speaking, nutrient cycling in IAS systems reduces the amount of wastes generated as crop residues are used to feed livestock and manure is returned to fields as an organic fertilizer. This closed loop of nutrients increases the efficiency of nutrient use, reduces pollution of the environment and production costs. Mixed crop-livestock operations have an improved nutrient-use efficiency and lower nutrient losses from leaching and runoff, leading to improved soil productivity and ecological sustainability over time when compared with conventional farming systems.

The integrated ecosystem service assessment framework for mixed crop-livestock farming systems is shown in Figure 1. The framework classifies ecosystem services as provisioning, regulating, supporting and cultural services and integrates indicator assessments focusing on the ecological, environmental, economic and technological aspects. It illustrates the soil health advantages of integrated crop-livestock systems, along with increased biodiversity, water resource management, carbon sequestration and resource-use efficiency. The framework emphasizes that the continuous assessment process, employing the latest tools, including the use of GIS, remote sensing, precision agriculture and multi-criteria decision analysis (MCDA), facilitates evidence-based decision making processes, in the end contributing to sustainable agriculture, the conservation of ecosystems, economic viability, and climate resilience.

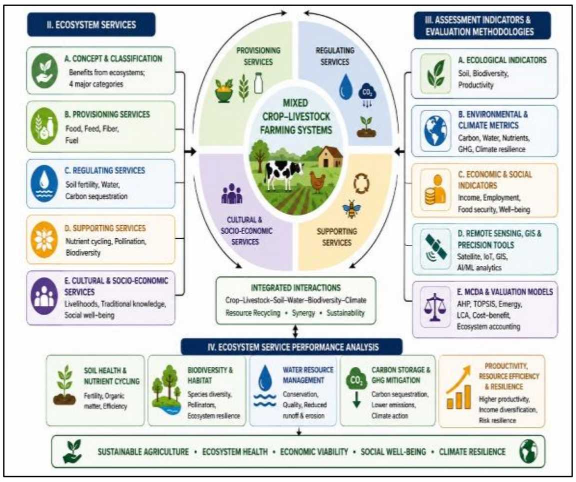

Figure 1. Ecosystem Services in Mixed Crop Livestock Farming Systems

Incorporating both crop and livestock production in a farming system can benefit biodiversity as it supports a wide range of plant, insect, bird, microbe and animal habitats. Integrated systems use several crop or species mixtures, pasture, hedgerows, agroforestry and grazing areas, providing the ecological diversity of the landscape.The integrated systems contain multiple crop species, pasture, hedgerows, agroforestry and pasture/grass areas, providing ecological diversity on the landscape. Greater biodiversity makes ecosystems more resilient, bolsters food chains and helps to make agricultural production systems more stable. Pollinators, natural predators and beneficial soil microorganisms are part of the ecosystem and are essential for maintaining balance of the ecosystem by providing better pollination, controlling pests naturally, and speeding up the decomposition of organic matter. Habitat diversity will also help to limit the likelihood of pest infestations and diseases, and limit dependence on pesticides. Preservation of native vegetation, along with sustainable grazing improves ecological connectivity and helps to support local flora and fauna. The conservation of biodiversity therefore helps to increase the functioning of the ecosystems and supports sustainable agricultural production.

Water has been a key limitation for agricultural productivity in the context of variable climatic conditions, and efficient management of water is crucial for this. Diversity of vegetation cover, reduction of surface runoff and better soil structure and organic matter content benefits the water use efficiency of mixed crop-livestock farming systems. Better infiltration rates of soils will promote groundwater recharge and reduce the erosion potential of soils and sediment transport. Using livestock manure as organic fertilizer will help keep the water in the soil and decrease the amount of irrigation needed. Water bodies are further shielded from sediments and nutrients by vegetative buffer strips and grasslands that filter out sediments and nutrients from the water before they can enter streams and lakes. Proper grazing practices reduce overgrazing and degradation of watersheds, which helps to achieve better watershed health. The use of integrated water management practices thus improves water availability, the quality of water and improves climate variability and drought resilience of the farming systems.

Reducing GHGs emissions is a top goal of sustainable agriculture, and mixed crop/livestock systems have significant potential to achieve that reduction. Manure application, conservation tillage, and cover cropping and agroforestry are all practices that increase the amount of soil organic carbon sequestered over long timeframes. Tree-based farming systems and pastureland have significant potential to hold carbon in the atmosphere, as well as enhancing soil health and biodiversity. Excessive use of chemical fertilizers is minimised by the use of integrated nutrient management, which will reduce the amount of N2O released. Avoiding waste burning and methane emissions through the recycling of agricultural residues in livestock feed or biogas production. Efficient livestock feeding strategies and improved manure management also help minimise greenhouse gas emissions. All these practices help to reduce carbon footprints and to support national and global climate change mitigation goals.Mixed crop-livestock production systems have a number of advantages, with one of the most important being the potential for greater productivity in agriculture and increased efficiency in the use of resources. Crop and livestock systems are complementary, with the output of one system becoming an input to another. Crop residues are used for animal feed; livestock manure is used as a soil amendment; and a diversified production system utilizes the land, water, labour and energy more efficiently.

The use of recycled resources has marked reductions in the amount of external inputs needed, production costs, and economic profitability. Agro-business diversification, that is, diversification across several agricultural products, such as grains, vegetables, fruits, milk, meat, eggs, fiber and renewable energy, helps to lower farmers' financial risks associated with market fluctuations and adverse climatic events. The ecological complexity and adaptive management practices of diversified farming systems also make them more resilient to droughts, floods, pest outbreaks and epidemic outbreaks of disease. Overall, mixed crop-livestock farming systems are found to be better performing than the specialized farming systems across ecological, environmental and economic aspects. They are a very powerful way of achieving sustainable agricultural development and having the potential to positively influence soil health, the conservation of biodiversity, water resources, climate change and farm resilience. However, for them to reach their full potential, integrated monitoring systems, scientific management, supportive agricultural policies, and ongoing innovation and adoption of advanced technologies to improve the delivery of ecosystem services and ensure long-term sustainability are essential.

VI. Proposed Integrated Ecosystem Service Assessment Framework

A. Framework Objectives and Design Principles

The Integrated Ecosystem Service Assessment Framework (IEAF) proposed here aims to offer a holistic methodology to assess the delivered ecological, environmental, economic and social values of mixed crop-livestock farming systems. The proposed framework breaks away from the traditional approach to assessment that operates at the level of individual indicators to provide an integrated assessment model for multiple ecosystem services. The purpose of the framework is to enhance the sustainability assessment by integrating ecosystem monitoring, resource-use analysis, environmental performance evaluation, and intelligent decision support. Main goals are to boost agricultural productivity, to conserve natural resources, to increase ecosystem resilience and to inform policy making based on evidence. The five design principles that are used in the framework are: the principle of ecosystem integration, the principle of resource efficiency, the principle of environmental sustainability, the principle of technological innovation and the principle of adaptive management. The principles attempt to make sure all the components of the ecosystem (crops, livestock, soil, water, biodiversity and climate) are assessed together to provide a holistic picture of the performance of farming systems.

The proposed integrated ecosystem service assessment model for mixed crop-livestock farming systems is shown in figure 2.

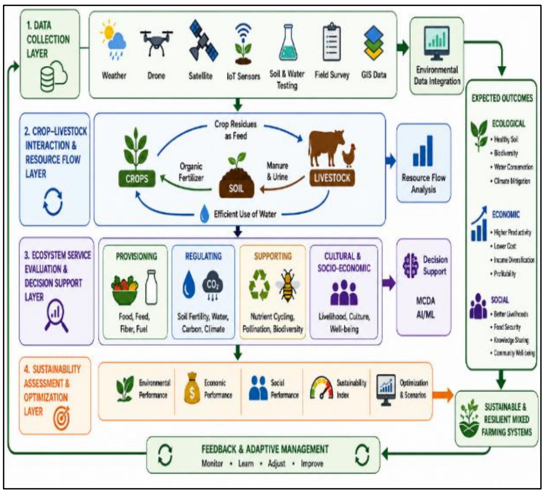

Figure 2. Proposed Integrated Ecosystem Service Assessment Model

The framework is four layered and interwoven: data collection, crop-livestock interaction and resource flow, assessment of ecosystem services, sustainability assessment and optimization. Environmental data from the sensors, GIS, remote sensing and field surveys are used to facilitate the analysis of resource flows in a crop-livestock-soil-water-ecosystems. Provisioning, regulating, supporting, and cultural ecosystem services are then assessed through decision-support methods, like MCDA and AI/ML, within the framework. Lastly, the indicators for sustainability are maximized for ecological health, economic performance and social well-being. Adaptive management is possible because of a continuous feedback mechanism which allows for resilient and sustainable mixed crop-livestock farming systems.

B. Data Acquisition and Environmental Monitoring Layer

The first level of the framework is to gather accurate and dependable data from various sources related to the environment and agriculture. These critical ecosystem variables are continuously monitored through field observations, soil testing, weather stations, satellite imagery, drone surveys and Internet of Things (IoT)-based sensors. Soil moisture, soil organic carbon, nutrient levels, vegetation health, crop growth, livestock productivity, and rainfall, temperature, humidity, and water quality are among the important parameters. The spatial information on land use, vegetation cover, distribution of biodiversity and watershed condition comes from remote sensing and Geographic Information Systems (GIS). Environmental monitoring that is carried out on a continuous basis will help to identify ecological changes early and respond to them in time. The compiled datasets are used as the input for assessing the ecosystem services and sustainability.

C. Crop-Livestock Interaction and Resource Flow Layer

The second layer represents the interactions between the crops, livestock, soil, water and natural resources in the integrated farming system. Crop residues are moved for use as livestock food and livestock manure is used as an organic fertiliser to enhance soil fertility. Water resources are developed optimally for farming, animal husbandry and ecological purposes. This resource flow layer assesses nutrient recycling, energy use, biomass conversion, carbon flow and water-use efficiency across the farming system. The framework identifies synergies between the different agricultural components, to reduce waste generation, better use of resources and strengthen the functioning of the ecosystem. Circular resource management also helps to reduce reliance on external agricultural inputs and enhance the sustainability of the farms.

D. Ecosystem Service Evaluation and Decision Support Layer

The ecosystem service evaluation layer is an analysis of the performance of mixed farming systems based on several sustainability indicators. Provisioning services assessed by: Crop yield, Livestock productivity, Food production, Income generation. Services that are regulated: soil fertility improvement, carbon sequestration, climate regulation, water conservation and erosion control. The services that are used to evaluate supporting services include biodiversity conservation, nutrient cycling, pollination and habitat quality, whereas cultural services include the rural livelihood, traditional knowledge, employment opportunities, and community wellbeing. It also integrates Multi-Criteria Decision Analysis (MCDA), ecosystem valuation approaches, artificial intelligence and machine learning algorithms to process vast amounts of environmental data and rank sustainable management options. Decision-support tools help farmers, researchers and policy makers make better decisions about what practices to use that maximise ecosystem services and minimise environmental impacts.

E. Sustainability Assessment and Optimization Module

The sustainability assessment module brings together ecological, environmental and economic indicators and social indicators to provide a full sustainability assessment. The performance indicators include carbon footprint, water-use efficiency, biodiversity index, nutrient-use efficiency, farm profitability, energy efficiency, and livelihood resilience, which are then normalized and aggregated to get an overall sustainability score. Optimization algorithms determine the management approaches which maximize ecosystem services provided for while minimizing the use of resources and greenhouse gas emissions. Further, scenario analysis assesses the effects of the different farming practices on different climatic and economic scenarios. Through this adaptive optimization process, ongoing enhancement in farm management can be achieved and agricultural sustainability can be maintained in the long term.

F. Expected Ecological, Economic, and Social Outcomes

The benefits of implementing the proposed framework are expected to be high, ecological, economic and social. The framework is environmentally friendly, with the aim of achieving more fertile soils, higher biodiversity, better nutrient cycling, lower greenhouse gas, more water efficient and higher climate resilience. These enhancements help to improve the sustainability of agricultural systems and a healthier environment in the long term. Integrated resource management has been proven to improve farm productivity, cost of production, farm income diversification and farm resource use efficiency from an economic point of view. This helps the farmers become more profitable, while cutting down on the need for external inputs like commercial livestock feed and chemical fertilizers. Socially, the framework contributes to the rural livelihoods by providing employment, food security, knowledge sharing and community engagement for sustainable agriculture. In addition, the combination of modern digital technology and ecosystem-based management helps guide evidence-based policymaking, promote climate-smart agriculture and enable the shift towards resilient and sustainable mixed crop-livestock farming systems to achieve future food security and environmental conservation objectives.

VII. Comparative Analysis and Performance Evaluation

The integrated nutrient cycling and use of multiple production and resources, as well as improved environmental and economic performance of mixed crop-livestock farming systems, is demonstrated when compared to conventional farming. Crops and livestock complement each other, lowering external inputs in agriculture and enhancing soil fertility, biodiversity and farm resilience. The conventional ones are mostly based on intensive use of chemical fertilizers and dedicated production, which in turn leads to higher environmental impacts and lower ecological stability.

Parameter	**Conventional Farming**	**Mixed Crop-Livestock Farming**
Soil Fertility	Moderate	High
Nutrient Recycling	Low	Excellent
Biodiversity	Low	High
Carbon Sequestration	Low	High
Water Use Efficiency	Moderate	High
Farm Income Stability	Moderate	High
Climate Resilience	Moderate	Excellent
External Input Requirement	High	Low

Table 2. Comparison of Conventional and Mixed Crop-Livestock Farming Systems

The overall sustainability performance of conventional farming and mixed crop-livestock farming systems are compared with each other in Table 2. The results of the comparison demonstrate that mixed farming outperform the other farming systems in all the key indicators such as soil fertility, nutrient recycling, conservation of biodiversity, carbon sequestration, water-use efficiency, income stability and climate resilience. Moreover, it eliminates the need for external inputs in agriculture through the good practice of recycling of crop residues and livestock manure. Overall the table shows that the mixed crop-livestock farming system is more sustainable and resource-efficient than the conventional farming system.

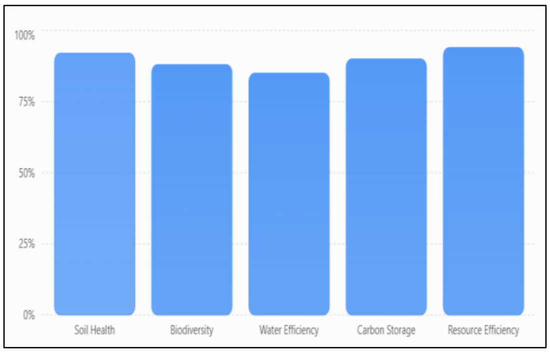

Figure 3. Comparative Sustainability Performance

The comparison shown in figure 3 demonstrates that the mixed crop-livestock system has consistently better results in all sustainability dimensions compared to conventional systems, especially regarding resource use efficiency, soil health and carbon sequestration.

The integrated farming systems significantly help to reduce environmental degradation by optimizing the nutrient recycling process and the management of resources. Diversified vegetation and soil fertility are improved by organic manure, and biodiversity is also enhanced by diversified vegetation. A decrease in the use of synthetic fertilizers leads to lower GHG emissions and ecosystem stability.

Indicator	**Conventional**	**Mixed System**
Soil Organic Carbon (%)	2.6	4.2
Carbon Sequestration (t/ha/year)	1.8	4.5
Water Use Efficiency (%)	65	88
Nutrient Recycling (%)	48	92
Biodiversity Index	0.52	0.84

Table 3. Environmental Performance Indicators

A conventional mixed crop-livestock farming system is defined as one that integrates both crops and livestock. Table 3 gives information on the environmental performance of the conventional and mixed crop-livestock farming system. The findings indicate that mixed farming system has higher soil organic carbon, carbon sequestration, water-use efficiency, nutrient recycling and biodiversity index than conventional farming system. The enhancements highlighted suggests that intercropping between crops and livestock can improve the overall health of the ecosystem, help sustain natural resources and minimize environmental effects, leading to more sustainable and resilient agriculture.

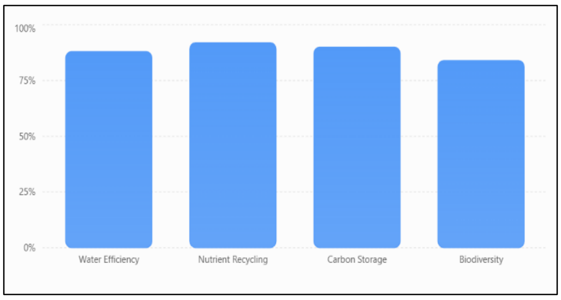

Figure 4. Environmental Performance Comparison

Based on the findings of Figure 4, it can be seen that integrated farming has a positive impact on environmental quality in the form of increased nutrient recycling efficiency, water conservation, and increased biodiversity.

The mixed farming systems increase the economic sustainability of farming by diversifying the farming products and lower production costs by using the internal recycling of the resources. Diversifying income sources can improve financial security and minimise climatic and market risks.

Indicator	**Conventional**	**Mixed System**
Annual Net Income (Index)	100	138
Input Cost Reduction (%)	—	28
Benefit-Cost Ratio	1.55	2.18
Income Diversification Score	42	91
Employment Generation	Moderate	High

Table 4. Economic Performance Comparison

Table 4 shows the economic performance of the conventional farming and the mixed crop-livestock farming systems. The findings show that the net income, benefit cost ratio, income diversification, production cost and employment opportunities are superior in the case of mixed farming system. The results indicate that the combination of crop and livestock enterprises increases the profitability of the farm, the financial stability of the agricultural household and its long-term economic sustainability.

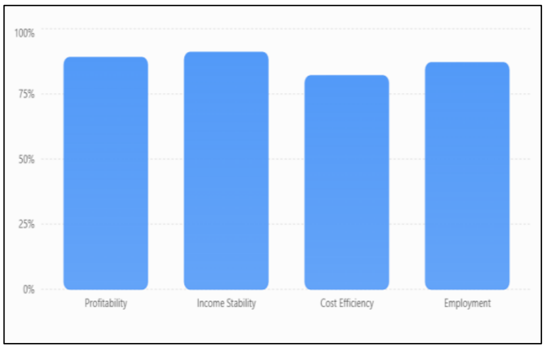

Figure 5. Economic Performance Analysis

As depicted in figure 5, the integrated farming system is more profitable, more income diversifying and more employment generating than other conventional farming system.

Mixed crop-livestock farming systems are able to deliver a range of ecosystem services at once, but there are some trade-offs that must be managed. Overloading by livestock and inadequate manure management can lead to water pollution. However, ecological synergies are produced when effective integration increases at the same time soil fertility, biodiversity, the carbon sequestration possibility and the productivity of farms.

Ecosystem Service	Major Synergy	Potential Trade-Off
Nutrient Cycling	Improved soil fertility	Excess manure accumulation
Biodiversity	Better pollination and pest control	Land competition
Water Conservation	Improved infiltration	Water demand during drought
Carbon Sequestration	Climate mitigation	Requires long-term management
Livestock Integration	Diversified income	Disease management

Table 5. Ecosystem Service Trade-Offs and Synergies

Table 5 describes the key synergies and trade-off of ecosystem services that are found in mixed crop-livestock farming systems. The table indicates that integrated farming contributes to increased soil fertility, biodiversity, water use efficiency, carbon sequestration and farm profits due to the efficient use of resources in recycling and the ecological interactions. It also points out some potential problems, including too much manure, competing uses for the land, water needs, and livestock disease control, that must be addressed through planning and sustainable practices. In overall terms, the benefits of the synergies far outweigh the disadvantages, leaving mixed crop-livestock farming as an extremely sustainable farming option.

Mixed crop-livestock production systems face barriers in the form of small land parcels, lack of technical expertise, and financial constraints, as well as the lack of policies that support farmers in adopting them. In addition, ecosystem service indicators are not yet standardized and monitoring systems are not well established. Artificial Intelligence, IoT, GIS, remote sensing, blockchain, digital twins and machine learning should be integrated in the ecosystem service assessment process for future research, which will facilitate real-time monitoring of sustainability and intelligent farm management. More robust sustainable agricultural planning and delivery of ecosystem services will be achieved by the evolution of global standardised assessment systems and climate-smart decision support systems.

VIII. Conclusion and Future Directions

Mixed crop-livestock farming systems are a sustainable farming method that provides an efficient use of farming resources, combining the production of crops and livestock to obtain maximum ecosystem services with minimum impacts. Integrated farming fosters efficient nutrient cycling, enhances soil fertility, supports biodiversity, manages water resources, and boosts carbon sequestration by combining resources, crops and livestock in a synergistic manner, compared to conventional farming practices. Such ecological processes help to increase agricultural production levels, enhance environmental sustainability, climate resilience and livelihoods in rural areas. The present paper analyzed in detail the ecosystem services provided by mixed croplivestock agriculture, such as provisioning services, regulating services, supporting services and cultural services. Integrated farming systems were assessed using different ecological, environmental, economic and social assessment indicators. The study also examined current ecosystem service assessment approaches, and identified the increased value of remote sensing, Geographic Information Systems (GIS), Internet of Things (IoT), artificial intelligence and Multi-Criteria Decision Analysis (MCDA) in the monitoring of ecosystems and in the evidence-based agricultural decisions. Comparative analysis showed that the mixed crop-livestock farming systems are superior in terms of resource-use efficiency, environmental protection, farm profitability, biodiversity conservation and adaptation to climate change compared to the conventional farming systems.

This paper introduced an Integrated Ecosystem Service Assessment Framework which integrates an ecosystem service evaluation, an ecosystem service optimization, an environmental monitoring system, a resource flow analysis system and an intelligent decision-support mechanism together in one framework to overcome the disadvantages of the current assessment methods. The framework helps facilitate adaptive management of farms and development of policies for sustainability because it uses current digital technologies to help facilitate continuous assessment of ecosystem performance and integrated ecological indicators. An integrated approach promotes overall assessment of agricultural sustainability and boosts the precision and reliability of the assessment of ecosystem services. Although these are considerable benefits, there are a number of obstacles to overcome to make the integrated croplivestock systems more widely adopted. However, limited funds, small parcels of holdings, poor technical skills, poor policy incentives, and unclear ecosystem service indicators remain as limiting factors in many agricultural areas. In addition, long-term environmental monitoring and extensive datasets are still scarce, and a comprehensive evaluation of sustainability is difficult.

Research can be carried out in the future through the development of intelligent, real-time platforms for assessment of ecosystem services, which combine Artificial Intelligence, Machine Learning, Digital Twins, Blockchain, Remote sensing, UAVs, IoT sensors and cloud-based Decision Support Systems. Standardization of indicators and predictive sustainability models for the provision of ecosystem services globally will enhance the comparability of agricultural systems in various geographical regions. Furthermore, integrating climate adaptation measures, precision agriculture technologies and principles of circular bio-economy into the ecosystem assessment framework will further enhance the resilience of mixed farming systems in the face of climate change.

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