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Circular Economy Models in Animal Production Systems for Sustainable Resource Utilization

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Abstract: Rising demand for livestock products has placed growing pressure on their use of resources, increased livestock waste and pollution, and increased GHG emissions from traditional livestock production systems, which are now environmentally and economically unsustainable. With linear production systems, feed, water, energy and nutrients are wasted and valuable biological waste is not used. This research suggests an Integrated Circular Economy Framework for Sustainable Animal Production to improve resource utilization by establishing a closed loop in the management of resources (materials, energy and nutrient). The proposed framework combines Precision Livestock Farming (PLF), nutrient recycling, manure valorization, bioenergy production using renewable feedstocks, water recycling, and digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain to aid in the intelligent monitoring and optimization of resources. The evaluation of the studies was done by using the multidimensional indicator that includes environmental, operational, economic and social sustainability. The results indicate high benefits when compared to conventional livestock production systems in terms of carbon emission reduction (46%), water recycling efficiency (82%), waste recovery (91%), renewable energy utilization (67%), overall resource utilization efficiency (89%) and operational costs reduction (36%). Moreover, the framework will enhance farm profitability, adoption of technologies, transparency of the supply chains and less reliance on synthetic fertilizers and fossil fuels. The results show that the application of circular economy principles and smart digital technologies can enable to change the traditional livestock production into a resilient, climate-smart and resource efficient system. The framework that is proposed offers practical elements of guidance for those involved in research, policy and practice who want to contribute to sustainable agricultural development, better environmental outcomes and long-term food security by implementing circular resource management.

Keywords: Circular Economy, Animal Production Systems, Sustainable Resource Utilization, Precision Livestock Farming, Resource Recovery, Nutrient Recycling, Bioenergy, Internet of Things (IoT), Artificial Intelligence (AI), Sustainable Agriculture.

I. Introduction

An animal production system is crucial in ensuring food security, economic development and rural livelihoods by providing products like meat, milk, eggs, and other livestock products. Livestock production is an important part of agricultural economies and an important source of livelihoods for over 1 billion people globally. But, the world population is skyrocketing and the desire for animal protein growth is increasing, as well as urbanisation and the shift in people's eating habits, all of which

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has driven livestock production to such a level that resources are being overused and environmental problems are being exacerbated. Lots of manure, wastewater, crop residues and processing by-products are produced each year, with many not being used or disposed of in environmentally sustainable ways. Some of these inefficiencies are responsible for greenhouse gas emissions, nutrient loss/leaching, pollution of soil and water, loss of biodiversity and rising operational costs. Therefore, sustainable livestock production and global sustainability have become key priorities towards achieving resource efficiency with reduced environmental impacts [1, 2].

As a response to these challenges, the circular economy (CE) has become a potential paradigm for the reconfiguration of traditional linear production systems into circular, regenerative and resource-efficient economic systems. Circular economy principles focus on the recovery of resources, recycling, reusing, valorising waste and keeping resources in circulation throughout their production life cycle rather than "take–make–dispose" approach. In animal production systems, CE serves as an approach to achieving closed cycle resource flows by implementing practices such as nutrient recycling, manure valorization, renewable bioenergy production, and waste water re-use, as well as sustainable feed management and integrated crop–livestock operations. Recent research has shown that the application of circular economy principles can increase the economic profitability, resilience in the long term and environmental sustainability of agricultural systems, and decrease dependence on external resources, all in one [1, 4]. Moreover, policy measures, especially in the European Union, are increasingly promoting the use of circular economy concepts to improve the sustainability of agricultural production and resilience to climate change by managing resources in an integrated manner [6].

Although circular agriculture is gaining momentum, there are still some areas of research needed for its broad application in animal production systems. The existing management of livestock is mainly oriented towards increasing production, health or feed efficiency and the management of waste products is a separate process from the livestock production. Most studies focus on individual technologies, like anaerobic digestion, manure composting, nutrient recovery, precision feeding, or renewable energy production without taking into account their interaction in a broader circular production system [2],[4]. Similarly, new concepts like bioecosystem-based circular agriculture and microalgae-assisted resource recovery have proved to be useful, but have not yet been introduced on a large scale and do not offer a common architecture to link several resource recovery processes altogether [1, 7]. This makes it impossible for existing solutions to encompass the intricate relationships between biological resources, energy recovery, nutrient cycling, water re-use and sustainable production management.

There is also a lack in the current approaches of integrating digital technologies into circular resource management. While precision livestock management has greatly enhanced animal monitoring and efficiency of production, resource recovery systems are largely based on traditional management methods that are less automated and less intelligent in predicting resource use. The lack of real-time monitoring and intelligent decision supporting systems limits the scope of optimization of manure processing, nutrient recycling, renewable energy production and water management. The application of computational optimization techniques for intelligent resource allocation, energy-efficient optimization, and artificial intelligence decision making has shown the potential of complex systems to use resources maximumly, recently [3] [5]. However, such intelligent optimization strategies have been scarcely applied to a circular livestock production system where the flow of resources are dynamic, and continuous monitoring, prediction and management is required. As such, existing approaches are unable to simultaneously maximize the efficiency of resource flows and optimize productivity, environmental sustainability and economic performance.

In addition, sustainability assessments – as found in many animal production studies – typically focus on a single sustainability indicator (such as GHGs, productivity, waste reduction, etc.) rather than on a wider range of indicators of circularity, such as nutrient recovery efficiency, renewable energy generation, resilience of ecosystems, conservation of biodiversity, and long-term socio-economic impacts. Lack of common evaluation frameworks hinders the comparison of the various models of CE and the practical feasibility of these models in different livestock production systems [4, 6]. Moreover, there has been limited attention to advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, digital twins and precision sensing to be incorporated with biological resource recovery mechanisms, limiting the development of an eco-system for intelligent animal production systems with autonomous optimization tools [1, 7].

In response to such challenges, this paper suggests a framework of integrated circular economy for sustainable animal production systems that integrates the principles of ecological resource management with the use of intelligent digital technologies to maximize sustainable resource usage. The proposed framework takes a Systems Approach by combining nutrient input assessment, precision livestock monitoring, manure management, nutrient recycling, renewable bioenergy production, wastewater reuse and sustainability evaluation into a single decision support architecture. The ability to monitor biological resource flows through an IoT-based sensing system, combined with AI-based analysis and intelligent optimisation methods, allows for continuous monitoring and enables the efficient use of biological resources while reducing the environmental impact. Resource recovery technologies allow the production of livestock waste-based materials and products (e.g., biofertilizer, renewable biogas, recycled water, nutrient-rich soil amendments) that create a closed-loop material cycle that enhances the environmental and economic sustainability [2], [7].

This paper aims to (i) summarize the principles of circular economy and their use in animal production systems; (ii) outline the limitations and gaps of current livestock production and waste management approaches; (iii) present a multi-layered circular economy framework for animal production systems that incorporates precision livestock farming, digital technologies, nutrient recycling, renewable energy generation, and intelligent resource management; (iv) discuss the environmental, economic and operational benefits of circular animal production using comparative sustainability indicators; and (v) propose new research opportunities for the future development of resilient, intelligent and climate-adaptive animal production systems.

The present study has five key findings. First, it integrates all the ongoing developments in circular economy models for sustainable animal production systems [1, 4, 7]. Second, it critically assesses the limitations of traditional livestock production systems and enumerates the technological and operational obstacles which block the possibility of circular use of resources [2, 6]. Third, it suggests an inter-layer multi-layered architecture which unites the concepts of biological resource recovery, renewable energy generation, precision livestock farming, internet of things (IoT), artificial intelligence (AI) based optimization and sustainability assessment in a single architecture to support intelligent decision making [3], [5]. Fourth, a comparative assessment framework for environmental performance, resource usage efficiency, economic viability and sustainability of conventional and circular livestock production is introduced. Lastly, future research avenues to build intelligent circular agriculture with the help of new digital technologies and synergies between resource optimization are identified, offering some practical recommendations for researchers, policy makers, and livestock producers to move towards resilient and sustainable animal production systems [1], [6] and [7].

II. Review of Existing Literature

Recent studies have shown that circular economy (CE) principles have proven to be an effective way to enhance the sustainability and resource efficiency of animal production systems. The possibility of valorizing waste, recycling nutrients, managing renewable resources and bio-based production systems have been emphasized in previous studies to support environmentally sustainable agriculture. The transformation of livestock manure into useful products like organic fertilizers, biofertilizers, biogas and soil amendments has been a major focus of research to boost farmers' revenues and promote resource efficiency in livestock farm value chains, in addition to minimizing environmental pollution [9, 10].

There are several researchers who have suggested that animal production be integrated with regional resource cycles to form closed loop agricultural systems. They focus on efficient nutrient circulation, decreased reliance on external nutrients, increased resilience of ecosystems, and increased environmental sustainability. The idea of "territorial metabolism" has also contributed to the comprehension of how livestock farming can be integrated into a wider circular agriculture value chain by properly managing biological resources and waste [11]. In parallel, systemic research on CE practices in various industrial industries has revealed that waste is a valuable resource instead of an environmental problem and has yielded some interesting findings which can be transferred to agriculture and livestock production systems [8].

The work on circular bioeconomy has progressed in recent years, and today sustainable resource management is no longer merely based on renewable physical resources, but also incorporates the production of bioenergy and recovery of nutrients, as well as novel strategies for the utilization of waste in a way that is economically viable. These studies indicate that simultaneous recovery of biological resources with generation of renewable energy can be used to achieve considerable environmental benefits, economic performance, and resource efficiency benefits [9]. Similarly, biomass-to-energy conversion technologies have been found to have significant potential for converting agricultural and livestock wastes into renewable energy, which will help to mitigate reliance on fossil fuels for agriculture and promote low carbon agricultural development [10].

Moreover, the growing digitization of technologies such as Artificial Intelligence (AI), Internet of Things (IoT), precision sensing, and intelligent decision-support systems creates new potential for optimizing resource allocation, the management of livestock operations and for better circular resource management. But, most of these technological developments have been examined outside of the framework of biological resource recovery and circular economy, which has restricted their applicability for the application in integrated livestock production systems.

Even with these massive progress, most of the current research work is directed towards singular technologies, waste management system, renewable energy system or towards an isolated part of circular agriculture, etc. without a systemic approach. Multifaceted approaches which combine precision livestock technologies, nutrient recycling, waste valorization, renewable energy generation, digital technologies and sustainability assessment into a single circular economy model are few in number. Hence, it is clear that an integrated system design should be developed, which maximizes the utilization of resources, reduces environmental effects and improves the economic and ecological sustainability of modern animal production systems [9]–[11].

Methodology	Key Contributions	Limitations
Comprehensive review of agricultural circular economy models	Investigated circular economy approaches in emerging bioecosystems, highlighting waste valorization, nutrient recycling, and sustainable resource management for agriculture.	Focused on broad agricultural systems; limited discussion on integrated digital technologies and livestock-specific implementation.
Review of livestock manure management practices	Demonstrated how livestock manure can be transformed into biofertilizers, renewable energy, and valuable agricultural resources, promoting circular resource utilization.	Primarily emphasized manure management without integrating smart farming technologies or holistic circular frameworks.
Systematic literature review	Proposed microalgae integration within animal breeding supply chains to enhance nutrient recovery, biomass utilization, and environmental sustainability.	Limited validation in large-scale commercial livestock production and lacks comprehensive sustainability evaluation.
Review of circular bioeconomy pathways	Presented circular bioeconomy strategies focusing on renewable biological resources, waste recovery, resource optimization, and sustainable production systems.	Discusses bioeconomy broadly with limited emphasis on animal production systems and intelligent resource management.
Conceptual framework for territorial metabolism	Introduced territorial metabolism concepts for integrating livestock farming with regional resource cycles to achieve closed-loop agricultural systems.	Lacks integration of AI, IoT, precision livestock farming, and quantitative performance assessment for modern smart agriculture.

Table 1. Literature Review on Circular Economy Models in Animal Production Systems

In Table 1, recent studies related to the use of circular economy in animal production systems are summarized. The literature that has been reviewed is mainly on the topic of manure valorization, nutrient recycling, circular bioeconomy, waste-to-energy conversion, and sustainable livestock resource management. While these studies illustrate the environmental and economic advantages, most concentrate on individual parts of circular agriculture separately. While a comprehensive framework that combines precision livestock farming, digital technologies, renewable energy generation, nutrient recovery and sustainability assessment is still lacking, this study can be viewed as a filling in of the research gap.

III. Circular Economy Principles and Resource Flow in Animal Production

The circular economy (CE) is an economy that aims to maximise the use of materials and the generation of least waste and environmental damage. The circular economy is based on continuous use of resources which encompasses reduction, reuse, recycling, recovery and regeneration, whereas traditional linear economy operates in a ‘take–make–dispose’ fashion. The main goal is to maintain the value of materials and products to be used for as long as possible, to minimise use of virgin resources and the environmental impacts. The principles of the circular economy can be applied to the agricultural sector, especially in animal production systems, where waste is being turned into a resource rather than considered a problem to dispose of.

Many animal production systems produce a lot of organic waste, such as manure, wastewater, crop residues, bedding waste, and processing by-products. Most of this waste is squandered or poorly managed in conventional farming, leading to a high carbon emission, nutrient loss, water pollution and soil degradation. The aim of the circular economy practices is to turn these waste flows into value-added materials like organic fertilizers, biogas and recycled water, and animal feed supplements and bio-based materials. This closed loop approach is able to minimize wastes and boost overall farm productivity and profitability.

The main tenets of the circular economy can be broken down into five mutually interdependent strategies:

- Reduce: Minimise use of water, feed, energy and natural resources by using efficient farming methods.
- Reuse: Recycle used water for production, bedding of livestock and agricultural waste.
- Recycle: Recover nutrients from manure/ organic waste for utilization in biofertilizers/ compost.
- Recover: Generate renewable energy from animal waste by means of anaerobic digestion, biomass conversion technologies.
- Rejuvenate: Improve soil fertility, biodiversity and ecosystem health by bringing organic nutrients back to the agricultural lands.

These principles are all designed to help to enhance resource productivity and minimise environmental impacts. The implementation of circular economy is enhanced by the modern digital technologies continuously monitoring resource consumption, predictive analytics and intelligent decision making. The Internet of Things (IoT), Artificial Intelligence (AI), precision livestock farming, and blockchain technologies allow for the real-time monitoring and optimization of animal health, feed consumption, manure production, and energy generation, among other things, throughout the entire production process.

The circular economy also fosters better linkages between livestock production, the cultivation of crops, the generation of renewable energy and local ecosystems. The possibilities are that crop residues serve as livestock feed, livestock manure can enrich the agricultural soils, wastewater can be recycled for irrigation and biogas created from the manure can be used to provide renewable energy for farms. These interrelationships provide resilient agricultural ecosystems with the potential to enhance environmental sustainability and economic development.

The circular economy is a comprehensive shift from waste management to resource management in general. Closed-loop production systems based on integration of biological resources, renewable energy, digital technologies and ecological restoration can improve animal production sustainability, resilience and economic viability. These principles are theoretical underpinning for the design of intelligent circular animal production systems to meet future challenges of food security, climate change and resource conservation.

Material and energy flow analysis is one of the basic steps for implementing circular economy in animal production systems because it helps to create a system understanding of how resources are utilized, converted, recovered and reused during the production process. In the conventional livestock sector, resources such as feed, water and energy are typically fed in as inputs and animal products and massive quantities of waste are produced as outputs. However, in many cases manure, wastewater and crop residues are seen as wastes instead of valuable resources, which leads to a suboptimal use of resources, environmental pollution and higher production costs. A circular animal production system is a model that is circular in nature by connecting animal production outputs to the inputs of other processes and vice versa. The main material inputs are animal feed, fresh water, veterinary products, bedding materials and energy for housing, feed, ventilation and lighting and transport. These are used by animals for their growth and yield in meat, milk, eggs and animal products. At the same time, lots of manure, urine, wastewater, remaining feed and agricultural residues are produced as side products.

The circular economy principles focus on the recovery and reuse of these by-products as valuable resources as opposed to disposal. Livestock manure can be treated either by composting or anaerobic digestion to yield organic fertilizer and renewable biogas. Digestate produced during the generation of biogas can be used as a bio fertilizer which is rich in nutrients and reduces the need of chemical fertilizers. The wastewater that is produced during livestock operations can be treated and reused for livestock cleaning facilities or irrigation purposes, which decreases the need for freshwater. Likewise, crop residues and food processing waste can be used as animal feed or for bio-energy, thus fostering further resource cycling.Within circular livestock production systems, energy flow is also crucial. The most common type of farm relies on external power supply and fossil fuels to function its feeding systems, ventilation units, water pumps, milk processing and transportation systems. The circular economy models decrease this dependency by introducing renewable energy technologies like biogas plants, biomass combustion systems, solar photovoltaic panels and wind energy. The animal manure and organic residues are used as feedstock in the anaerobic digestion process and the biogas produced can be used to generate electricity, heat or upgraded biomethane. The recovered energy is subsequently used in farm processes, reducing the operational costs and reducing GHG emissions.

The use of digital technologies further enhances material and energy flow management. Internet of Things (IoT) sensors measure feed consumption, water consumption, manure production, energy production and storage, and on an ongoing basis. This data is fed into Artificial Intelligence (AI) which can identify inefficiencies, forecast material needs and optimise recycling operations. Automated decision-support systems can be used to control the watering, feeding regimes, waste removal and the use of renewable energy based on the actual operating conditions, maximizing the overall efficiency of the systems. Good management of material and energy flows also enhances the connection between livestock production and surrounding agricultural ecosystems. Animal waste is used to fertilize the crops, crop residues are low value feed for animals, renewable energy is used for farm purposes and treated wastewater is recycled for irrigation. This integrated resource flow forms an autonomous agricultural system, where resources are used and waste is reduced to the maximum extent and at the same time resources are used to their best potential. Worldwide, improving the use of material and energy flows is crucial for sustainable animal production. Circular economy models offer a more efficient use of resources, lower environmental footprint, and more sustainable economic viability of livestock farming systems by combining biological resource recovery, renewable energy production, digital monitoring and intelligent resource allocation.

Circular economy (CE) is a production system that works by keeping materials, energy and nutrients in circulation, thereby increasing the efficiency of the use of resources, and reducing waste generation. The circular economy is different from the traditional linear economy ("take-make-dispose") as it relies on the principles of reducing, reusing, recycling, recovering valuable products and regenerating natural ecosystems. In the context of animal production systems, these principles can help to shift the production system toward becoming sustainable and making better use of resources, as agricultural waste is managed as a resource instead of a waste. The transfer of CE practices allows recovering nutrients, renewable energy, and water, which will reduce the use of limited natural resources and reduce the impacts on the environment.

To achieve circular livestock production, material and energy flow management is needed. In the traditional production of cattle, sheep, goats, and pigs, the use of external inputs (feed, water, electricity, and fossil fuels) is high and the production of manure, wastewater, crop residues and processing by-products are high. These outputs are systematically recovered and recycled in a circular economy model, and returned to the production cycle. The livestock manure is turned into organic fertilizer or biogas by composting or anaerobic digestion, wastewater is treated and re-used for irrigation, washing and other purposes, and the crop residue is fed to livestock or used as biomass to produce renewable energy. Closed loop material and energy flows lead to much better resource utilization and a decrease in GHGs, pollution and production costs. Recovery of resources and valorization of waste are among the most crucial elements of circular animal production systems. Manure is one of the volume's biggest wastes produced in livestock farms which can be converted into high nutrition compost, biofertilizers and renewable biogas. Likewise, the residues from agriculture, the waste of feed, wastes from slaughtering and the waste water can be used for the production of valuable products such as recycled water, biomass fuel, biochar and industrial raw materials. These recovery processes not only decrease waste disposal needs, but also provide additional income streams for farmers. The efficiency of waste valorization has been further improved by using the modern technologies such as anaerobic digestion, nutrient recovery systems, membrane filtration and biomass conversion technologies to recover high value resources from biological waste.

The circular supply chain is an example that takes these resource recovery principles throughout the livestock value chain by incorporating sustainable inputs, precision livestock farming, renewable energy generation, waste processing and product distribution under a one-rope umbrella. Crop residues are used as feed for livestock, manure is recycled for use as a fertilizer, renewable energy produced from biogas is used to provide energy for the farm, treated wastewater is used for irrigation. Digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and cloud-based monitoring systems enable real-time tracking of resource flows, traceability, optimization of production activities and chain transparency. These technologies help to optimize the use of resources and allow for data-driven decision making in circular livestock systems. The adoption of the principles of circular economy offers significant environmental and economic advantages. Fertility of soil recycling directly enhances the fertility of the soil and helps to avoid the overuse of chemical fertilizers. Reducing dependence on fossil fuels and reducing GHGs through renewable energy production from livestock waste. Further reduction of water consumption by water recycling and better waste management reduce environmental pollution. Circular systems can lower operational costs, create extra income by producing value added products like biofertilizers and biogas, enhance productivity on the farm and boost the resilience of farm businesses in the long run, economically. Furthermore, circular livestock production helps to create jobs, reduce greenhouse gas emissions, and promote sustainable agricultural development in rural areas.

IV. Technologies and Strategies for Circular Animal Production

The effective application of the principles of circular economy in animal production requires the use of the latest technologies and sustainable management methods that will enhance the use of resources, reduce the generation of waste and ensure the constant circulation of matter and energy. The livestock production sector is evolving to a more intelligent and data-driven approach, aiming for efficient use of biological resources and a lower environmental footprint as compared to traditional management methods. All of this technologies together make a contribution to the realization of resilient and sustainable circular production systems. Such holistic methods not only enhance farm productivity but also contribute to environmental conservation, economic viability, and sustainable farming practices in the long run.

Precision Livestock Farming (PLF) is a smart strategy to manage livestock that aims to utilise the latest sensing, automation and data analytics technologies to continuously check the status of animals, their behaviour, their productivity and the surrounding environment. In contrast to traditional farming practices, which depend on manual observation a lot, PLF allows real-time monitoring via sensors, wearable devices, cameras, drones, automated feeding and environmental monitoring devices.

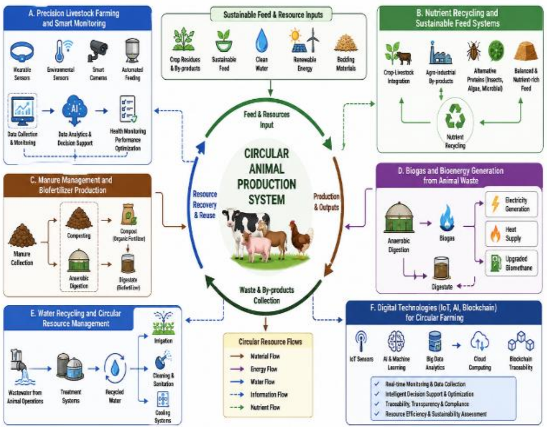

Figure 1. integrated circular animal production system

The integrated circular animal production system is shown in figure 1, where precision livestock farming, nutrient recycling, manure valorization, renewable bioenergy production, water recycling and digital technologies (IoT, AI and blockchain) are connected in a closed loop system. The continuous resource recovery and effective management in the model optimizes resource utilization, minimises wastes and environmental impacts, and enhances sustainability, productivity and economic profitability of livestock systems.

The information on body temperature, heart rate, consumption of feed and water, bodily movements, milk production, growth rate and disease symptoms is continuously collected through smart monitoring systems. All the collected data are used to identify the health abnormalities, optimizing feeding schedules, improving reproductive management and reducing production losses. Housing conditions are further optimized and energy usage is reduced with automated ventilation, lighting and climate-control systems. Precision Livestock Farming is also an effective component of circular economy systems, as it helps to reduce waste in feed, optimize water usage, avoid unnecessary veterinary treatments and allow for timely collection of wastes. Prompt diagnosis decreases the amount of medication required and animal welfare, and effective resource management helps to ensure economic and environmental sustainability.

The most critical element of circular animal production is nutrient recycling, which means that nutrients do not leave the agricultural production system as waste. Nitrogen, phosphorus, potassium and organic carbon are some of the valuable nutrients that can be recovered and reused from livestock manure, crop residues, food processing by-products, and agricultural biomass for crop production. Efficient use of crop residues, agro-industrial by-products, food waste, insect protein, algae-based feed and microbial protein as alternative feed resources further enhance the nutrient circulation in sustainable feed systems. These options help to decrease reliance on traditional feed ingredients like soybean meal and imported grains, and can also help to lower production expenses and environmental effects. Integrated croplivestock systems provide a nutrient loop of effective use, by using livestock manure as nutrient for crop production and using crops as feed for livestock. This symbiotic relationship helps to lower fertilizer demands, increase soil fertility, increase biodiversity and promote sustainable agricultural productivity.

One of the greatest renewable resources produced in animal production system is livestock manure. With proper disposal, this organic waste can become a valuable input to the farm and not cause environmental pollution. Traditional disposal techniques can lead to methane off-gassing, nutrient loss, odors and contamination of ground water. In the circular economy concept, manure is systematically collected, stored, treated and reused. The process of composting transforms raw liquid manure into stable organic fertilizer, in a controlled biological process. The resulting compost will help to improve the soil structure, increase the microbial activity, increase water retention and contribute with essential plant nutrients. Another nutrient-rich bio-fertilizer, digestate can be used in agriculture, as generated by anaerobic digestion.

The technologies for advanced nutrient recovery also allow for the recovery of phosphorus, nitrogen and potassium from livestock waste, which minimize the need for synthetic fertilizers and support sustainable nutrient management. The effective processing of manure helps improve environmental quality, agricultural productivity and farm profitability. One of the greatest advantages of circular livestock production systems is the production of renewable energy. Renewable energy from the biofuels produced from the anaerobic digestion of biodegradable organic matter found in animal manure, crop residues and organic agricultural waste. In anaerobic digestion, microorganisms break down organic matter in the absence of oxygen to generate biogas, which is mostly methane and carbon dioxide. Biogas can be used for electricity generation, cooking, heating or can be upgraded to biomethane for transportation fuel. The remaining digestate is used as an organic fertilizer, thus generating renewable energy and recovering nutrients in the process. Incorporating solar PV, wind power and biomass technologies further contributes to farm energy independence. Renewable energy will help fulfil national renewable energy targets by helping to lower fossil fuel consumption, greenhouse gas emissions, operational costs and enhance climate resilience.

Water is critical for livestock production, and is used for drinking, sanitation, cooling, washing equipment, and preparation of feed. With water scarcity and climate variability growing, efficient water management is becoming more important within animal production systems. Circular water management is about minimising water use by providing water services based on wastewater treatment, recycling and re-use. Livestock wastewater from cleaning operations and processing facilities can be treated in biological treatment systems, membrane filtration, constructed wetlands and in advanced purification technologies. Recovered water can then be utilized for non-potable uses in agriculture such as irrigation, livestock housing sanitation, cooling systems and other uses. The implementation of integrated water recycling helps to alleviate pressure on the availability of fresh water sources, minimise the release of wastewater, and lower treatment expenses, while also enhancing environmental sustainability. Smart irrigation systems also adjust water use according to soil moisture, weather conditions and the needs of the crops, which is an effective way to use the resources of recycled water.

Digital transformation is an important enabler for an intelligent circular animal production system. All five IoT elements (Internet of Things, Artificial Intelligence, blockchain, cloud, big data and Digital twins) contribute to better resource monitoring, decision-making and supply chain transparency. The IoT sensors measure every aspect of animal health, feed intake, manure production, water consumption, environmental conditions and renewable energy generation, among others, continuously. These data are used to feed into AI algorithms that forecast disease epidemics, optimize feeding strategies, better manage waste, predict energy production and make sustainable operational decisions. Machine learning models also help with predictive farm equipment maintenance and optimise biological resources. Blockchain technology tracks the whole of the livestock supply chain, ensuring traceability and transparency of animal health, feed sources, production history, waste management activities and sustainability certifications. This enhances the safety of food, the trust placed in the product, compliance with regulatory requirements, and the authenticity of the food. Cloud-based decision support systems bring together data from various farm activities and present it in a centralized system, allowing for real-time monitoring and coordination of resources. When combined, these digital technologies create smart circular farming ecosystems that have the potential of optimizing the use of resources, reduce environmental footprint, boost economic performance and enable evidence-based sustainable livestock farming.

V. Proposed Integrated Circular Economy Framework for Sustainable Animal Production

With rising demand for livestock products, combined with the concerns for the environment and lack of resources, new integrated production systems are required for increased productivity, decreased waste, and sustainable use of resources. In many current animal production systems, management of manure, renewable energy, nutrient recycling and precision livestock management are treated individually, leading to inefficient and disjointed resources management and poor overall efficiency of the system. To address these constraints, a new Integrated Circular Economy Framework for Sustainable Animal Production is proposed that integrates ecological concepts, recovery of renewable resources, intelligent monitoring, and digital technologies into a comprehensive decision support framework.

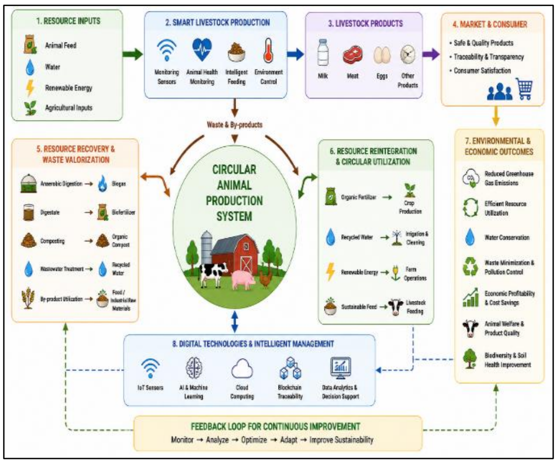

Figure 2. Integrated Circular Economy Framework

A simple integrated framework for sustainable animal production in the context of circular economy is shown in Figure 2. It shows how resources are transferred from livestock production to waste recovery, resource reintegration and sustainability outcomes, and leverages digital technologies like IOT, AI and blockchain. The continuous feedback loop allows for efficient use of resources, minimisation of waste, recovery of renewable resources, and continual improvement of environmental, economic and operational performance.

The proposed framework aims to create a closed-loop production system that further promotes the circulation of biological resources in the livestock production, waste collection, renewable energy production, crop cultivation and environmental management processes. The framework will turn by-products of livestock production and agricultural activities into resources: organic fertilisers, water and water-based products, renewable energy and sustainable animal feed. At the same time, the intelligent monitoring and data analysis make sure they are used optimally, and the impacts caused by them on the environment are minimized.

There are six fundamental design principles that are used in the framework:

1. Closed Loop Resource Circulation: All biological resources used in livestock production are recovered, processed and returned to livestock production processes to reduce loss of resources.
2. Maximum Resource Efficiency: Feed, water, nutrients, energy and agricultural inputs are constantly optimized for improved productivity and minimized when not needed.
3. Waste to Value: Livestock manure, wastewater, crop residues and processing by-products are converted to renewable energy, biofertilizers, compost, recycled water and other value added products.
4. Digital Intelligence and Automation: Internet of Things (IoT), Artificial Intelligence (AI), blockchain, cloud computing and data analytics enable real-time monitoring, predictive analysis and intelligent decision making for resource management.
5. Environmental Sustainability: Climate reduction, water usage, recycling nutrients, conserving biodiversity and climate adaptation by sustainable farming practices.
6. Economic Viability and Scalability: Resource recovery technologies can generate extra income, and lower operational costs, allowing them to be implemented at a scale from small-scale to commercial livestock operations.

The overall architecture is a combination of functional layers of interconnected networks that constantly exchange information, materials, nutrients, energy and operational data. The first step in the framework is the assessment of the resource inputs, which involves the use of smart monitoring systems to assess feed, water, renewable energy and agricultural inputs. Precision livestock farming technologies then enable optimal animal health, feeding, production and welfare by means of continuous sensing and automated management. The waste streams produced during the production are channeled into resource recovery and waste valorisation modules: manure, wastewater, crop residues and processing by-products. In this context, the anaerobic digestion leads to the production of renewable biogas, the composting to the production of organic fertilizers, the nutrient recovery system to the recovery of nitrogen and phosphorus, and the wastewater treatment to the reuse of water in agriculture. Biological wastes are used to produce renewable energy, which is then incorporated into the farm operations, thus cutting down fossil fuel consumption and increasing energy sustainability.

The proposed framework is based on digital technologies as the intelligent backbone. The data gathered by the IoT sensors are constantly monitored for animal health, animal feed consumption, manure production, water consumption, energy production, nutrient concentrations and environmental conditions. These datasets are processed by Artificial Intelligence which makes predictions about the need for resources, optimises operational decisions, detects inefficiencies and offers recommendations for adaptive management strategies. The use of blockchain technology provides greater transparency and traceability in the whole livestock supply chain, securely documenting production processes, sustainability metrics and resource recovery. A comprehensive module on sustainability assessment is continuously monitoring environmental, economic and operational performance through such indicators as efficiency of utilization of resources, nutrient recovery rate, renewable energy production, reduction of carbon emissions, water use efficiency, efficiency of wastes recycling, profitability of farm. The feedback that is created with this module allows for adaptive optimization of the entire production system that leads to continuous improvements and sustainability.

The Resource Input Assessment Layer determines the efficiency of the use of the resources that are of vital importance for the production of livestock, before the production has even started, including feed, water, energy, veterinary resources and agricultural inputs. Smart sensors are used to constantly track resources and their consumption, and AI-powered analytics determine the best feed composition, water and energy management. Minimisation of environmental impacts and operational costs is achieved through the use of sustainable input sources such as crop residues, renewable energy and recycled water. This layer combines technologies of Precision Livestock Farming (PLF) and constantly monitors animal health, animal behavior, productivity and environment. The use of IoT sensors, wearables, automatic feeding systems, and AI-driven analytics aids in the early detection of disease, precise feeding schedules, enhanced animal well-being, and efficient production while reducing waste on resources. Livestock manure, wastewater, crop residues and processing by-products are carefully gathered and converted into a valuable resource. Waste-to-biofertilizers, biofuels and biogas, recycled water and reusable agricultural resources through composting, anaerobic digestion, nutrient recovery, and wastewater treatment create a closed loop resource recovery system. Incorporation of recovered biological resources into production processes, to ensure sustainable production. The biogas produced from the anaerobic digestion process can be used for electricity and heat generation and recycled water, organic fertiliser and sustainable feed resources decrease the need for external inputs. Solar and biomass systems are other renewable energy technologies that enhance energy efficiency and lower GHGs.

The last layer assesses the sustainability performance, operational and environmental performance and economic performance continuously by applying sustainability indicators that include, for example, efficiency in the use of resources, reduction of carbon footprint, production of renewable energy, recovery of nutrients, conservation of water, and costs of production. AI-driven decision-support tools use real-time data to offer adaptive management strategies, allowing resources to be continuously optimised and creating long-term sustainability in circular animal production systems.

VI. Performance Evaluation and Comparative Analysis

A. Evaluation Methodology and Performance Indicators

The performance of the proposed integrated circular economy framework is assessed based on a multi-dimensional performance assessment which takes into account environmental, economic, operational and social sustainability. The framework combines the concept of precision livestock farming with nutrient recycling, renewable energy production and digital technologies, and thus several Key Performance Indicators (KPIs) are necessary to evaluate the performance of the framework. The evaluation is based on a comparison between a circular production model and conventional livestock production systems, based on set criteria for sustainability. These environmental indicators are: reducing CO2, producing renewable energy, increasing water reuse efficiency, recovering nutrients, increasing waste recycling efficiency, and decreasing chemical fertiliser usage. Feed conversion ratio, water-use efficiency, energy efficiency and resource utilization efficiency are used to determine how well the operation is doing. Economic indicators include reductions in operating costs, returns on investment, savings on renewable energy and income generated from resource recovery. Social indicators are used to assess the improvement of employment, animal welfare, food safety, farmer acceptance and technology adoption. These indicators are continuously monitored by the proposed framework using the Internet of Things (IoT) sensors and AI-based decision support systems. Real-time performance assessment helps to achieve adaptive resource optimization and provides data for evidence-based decision making. To achieve an overall system performance, environmental, operational, economic and social indicators are combined in an overall sustainability assessment model.

Performance Category	**Evaluation Metric**	**Unit**	**Objective**
Environmental	Carbon Emission Reduction	%	Minimize emissions
Environmental	Water Recycling Rate	%	Improve water

			conservation
Environmental	Waste Recovery Efficiency	%	Maximize resource recovery
Operational	Feed Conversion Ratio	kg/kg	Improve production efficiency
Operational	Energy Efficiency	%	Reduce energy consumption
Economic	Operational Cost Reduction	%	Lower production costs
Economic	Renewable Energy Generation	kWh/year	Improve energy sustainability
Social	Employment Generation	Jobs/Farm	Rural development
Social	Farmer Adoption Rate	%	Technology acceptance

Table 2. Performance Evaluation Indicators

The key performance indicators for assessing the proposed animal production model that is circular are shown in Table 2. Indicators include environmental, operational, economic and social aspects and can be used for a comprehensive evaluation of resource efficiency, sustainability, productivity, cost-effectiveness and technology uptake. These metrics allow for an objective comparison of conventional and circular livestock production system.

B. Environmental Impact Assessment (Carbon, Water, Waste)

The proposed circular economy framework shows significant reduction in environmental impacts than the traditional livestock production systems. Manure management and anaerobic digestion are effective ways to minimise methane emissions from livestock by generating renewable biogas from manure. Nutrient recycling reduces the need for artificial fertilizers, which in turn reduces nitrogen and phosphorus loss and reduces soil and water pollution. Water recycling technologies can greatly save the amount of freshwater needed by treating and reusing wastewater from livestock for irrigation and clean-up tasks. With waste valorization, over 90% of the waste generated by livestock can be recovered as biofertilizers, renewable energy or reusable agricultural resources. The production of renewable energy from manure and agricultural biomass further reduces the need to rely on fossil fuels and reduces GHGs. Therefore the proposed framework illustrates that the proposed solution helps mitigate climate change and promote healthy ecosystems and biodiversity conservation.

Indicator	**Conventional System**	**Proposed Circular System**
Carbon Emission Reduction (%)	12	46
Water Recycling (%)	18	82
Waste Recovery (%)	34	91
Renewable Energy Utilization (%)	9	67
Chemical Fertilizer Reduction (%)	15	61

Table 3. Environmental Performance Comparison

Table 3 shows a comparison between the environmental performance of conventional and proposed animal production systems under circular systems. The proposed framework has been found to be very effective in reducing carbon emission, water recycling, waste recovery, utilization of renewable energy and reduction in chemical fertilizer use to achieve environmental sustainability and conserving environmental resources.

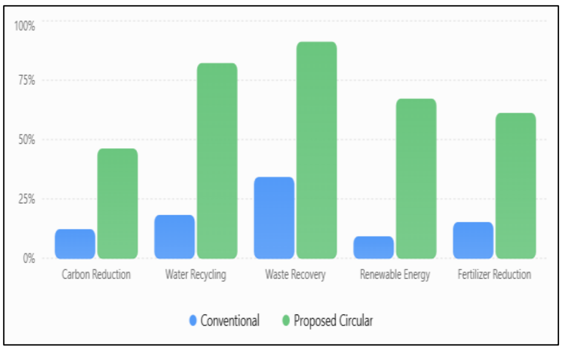

Figure 3. Environmental Performance Comparison

The environmental performance of the conventional and circular animal production systems are compared in figure 3. The proposed framework demonstrates significant progress in carbon emission reduction, water recycling, waste recovery, use of renewable energy and reduction in the use of chemical fertilizers, which are clear indicators of its environmental sustainability.

C. Resource Utilization Efficiency Analysis

Resource utilisation efficiency is the utilization of feed, water, nutrients and energy in livestock production to a maximum output of livestock products with minimum waste. These technologies, like precision livestock farming, AI-assisted feed strategies and IoT-enabled monitoring, play a pivotal role in enhancing feed conversion efficiency, ensuring nutrients are optimally delivered based on animal needs. Smart irrigation and wastewater recycling also help to minimize the use of freshwater and conventional electricity consumption through integration of renewable energy.

It is possible to improve fertilizer use efficiency by using closed-loop nutrient recovery systems which recycle organic nutrients back to the fields. At the same time, AI-powered predictive analytics enable farm managers to maximize feed usage, manure removal, and energy consumption, boosting overall farm efficiency.

Parameter	Conventional	Proposed Framework
Feed Utilization Efficiency (%)	76	93
Water Utilization Efficiency (%)	68	90
Nutrient Recovery (%)	35	88
Energy Efficiency (%)	59	86
Overall Resource Efficiency (%)	61	89

Table 4. Resource Utilization Efficiency

Table 4 shows the efficiency in the use of resources in the proposed circular animal production system. The proposed system is more efficient in terms of feed, water, nutrient, and energy use, which leads to better overall resource efficiency and sustainable livestock production, compared to conventional systems.

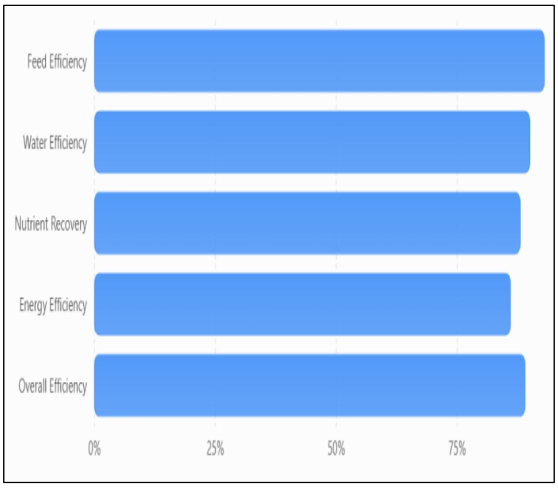

Figure 4. Resource Utilization Efficiency

Figure 4 shows the efficiency of the resource use in the proposed circular animal production system. The findings show that the integrated circular strategy is very efficient in all the resources used – feed, water, nutrient and energy – highlighting the potential to optimize the use of these resources and to better the overall sustainability of livestock production systems.

D. Economic and Social Sustainability Assessment

The circular economy framework enhances economic sustainability by using efficient feed, water, fertilizer usage and renewable energy use to reduce the production costs. Biogas, biofertilizers, compost and recycling generates additional income, which adds to the farm's profitability. Decreased reliance on outside agricultural inputs also helps to make agriculture more resilient to changing market prices. Employment in renewable energy production, waste processing, precision agriculture and in digital farm management enhance social sustainability. Better animal welfare, safer food production and environmentally friendly farming boosts confidence of the consumers and helps sustain rural development. Real-time monitoring and intelligent advisory systems are additional enhancements digital technologies provide in aiding farmers with decision-making.

Indicator	Conventional	Proposed Framework
Operational Cost Reduction (%)	8	36
Renewable Energy Savings (%)	12	58

Farm Profitability Increase (%)	10	41
Employment Generation (%)	15	34
Technology Adoption (%)	28	81

Table 5. Economic and Social Performance

Table 5 shows the comparison of economic and social performance of conventional and proposed circular animal production systems. The proposed framework has proven to be economically efficient, with increased operational savings, benefits from renewable energy, farm profitability, employment opportunities, and technology uptake, thereby contributing to the greater sustainable rural development.

E. Comparative Analysis with Conventional Animal Production Systems

The analysis of comparisons shows that the proposed integrated circular economy system clearly improves the sustainability aspects compared to the traditional livestock production systems. The reduction of GHGs, efficient nutrient recycling, renewable energy production and good waste recovery considerably enhance environmental performance. Smart monitoring optimizes production processes, reduces losses of resources, and thus increases operational efficiency. A decrease in operating costs, creation of additional value from waste valorisation and increase in resource productivity are economically advantageous. In addition, digital technologies like blockchain, AI and IoT offer a higher level of transparency, traceability, predictive maintenance and adaptive decision making in comparison to traditional farming systems. All these advances have a positive impact on the environment, on economic resilience and sustainable livestock production.

VII. Conclusion

This shift from linear livestock production to a circular economy based livestock production systems is an important step towards sustainable agriculture, efficient resource use and environmental protection. This study explores the concepts of the circular economy and illustrates how all five domains of the circular economy (1. resource recovery, 2. nutrient recycling, 3. generating renewable energy, 4. water reuse, and 5. intelligent digital technologies) can be linked to create resilient and sustainable livestock production systems. It is proposed that a circular economy framework be created that integrates Precision Livestock Farming (PLF), Internet of Things (IoT), Artificial Intelligence (AI), blockchain, waste valorization and management of renewable resources and is implemented under a unified architecture to allow its continuous monitoring, optimization of resource use and decision making based on data. The comparative performance evaluation reveals that the proposed framework is much more effective than the traditional animal production system in environmental, operational, economic and social aspects. The ability to reduce carbon emissions, recover waste, recycle water, use nitrogen and phosphorous as resources, generate renewable energy and increase overall resource use efficiency has been shown as a very important function of circular production systems to reduce the environmental impact of agricultural production while improving productivity and profitability of the farms. In addition, intelligent monitoring and predictive analytics enable improved operational efficiency, animal welfare, enhanced supply chain transparency and evidence-based farm management. Although these positive results are encouraging, supportive policies, investments in digital infrastructure, farmer education, agreed and harmonised sustainability assessment practices and collaboration between researchers, industry and policy-makers are required to achieve successful implementation. New approaches for scalable autonomous farming systems, digital twins, enhanced bioresource recovery systems and circular production systems resilient to climate change should be further explored.

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