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Original Research Paper

Sustainable Nutrient Recycling Strategies in Livestock Production within Circular Bioeconomy Frameworks

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Abstract: Recycling of nutrients is a critical solution that can help increase the productivity of livestock while decreasing the environmental impact and work towards the circular bioeconomy goals. There are a number of nutrient losses that can be introduced into the conventional livestock production system, such as manure mismanagement, Greenhouse Gas emissions, eutrophication and inefficient resource utilization. This review focuses on sustainable nutrient recycling strategies in livestock production systems that integrate concepts of circular resource management, crop–livestock interactions, and cutting-edge technologies for nutrient recovery. Nutrient flow pathways and the major sources of N, P and K, and their environmental impacts are discussed. It also examines sustainable technologies for improving nutrient use efficiency and renewable energy production, such as the collection and processing of animal manure (composting, vermicomposting, ANAEROBIC DIGESTION, BIOGAS production), as well as the recovery and reuse of nutrients from digestate and manure/wastewater. The proposed circular bioeconomy framework emphasises closed-loop recycling solutions which are low in waste and high in soil fertility, agricultural productivity and ecosystem sustainability. Moreover, there is a current discussion of technological constraints, monitoring problems, scalability aspects and the resilience in the face of climate change, followed by a discussion of future research needs. The adoption of precision agriculture, the use of artificial intelligence, monitoring with the Internet of Things and decision-support with data should further support adaptive nutrient management and recycling efficiency. All these integrated approaches can help build environment friendly, economically sustainable and climate resilient livestock production systems that can support global sustainable development and circular bioeconomy targets.

Keywords: Circular bioeconomy; Livestock production; Nutrient recycling; Anaerobic digestion; Composting; Precision agriculture; Sustainable agriculture.

I. Introduction

Livestock production is essential for food security, rural livelihoods and agricultural economic development globally as a source of meat, milk, eggs and other animal derived products to support the growing world population. But the ever growing and intensifying of livestock production has led to a substantial increase in nutrient inputs and wastes produced which present severe environmental and resource management problems. Nitrogen (N), phosphorus (P), potassium (K) and organic carbon are valuable nutrients that are found in large amounts in manure, wastewater and organic residues produced by livestock enterprises. However, if not managed efficiently they can lead to nutrient leaching, emissions of greenhouse gases, eutrophication of water bodies, soil degradation, smell pollution, and loss of biodiversity. Thus, the research and development of sustainable circular bioeconomy models has emerged as an important research focus to balance agricultural productivity

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and environmental conservation, as opposed to conventional linear production systems [1]. The circular bioeconomy aims to use the biological resources in the most efficient way possible by minimizing waste and instead recovering and regenerating them to create valuable products from the agricultural waste. In livestock production systems, the recycling of nutrients is one of the most crucial parts of circular resource management, as it allows for the multiple uses of nutrients without relying on synthetic fertilizers and environmental pollution. Recovery of nutrients from manure, slurry, digestate, wastewater and crop residues opens the possibility to close agricultural loops, by using the waste produced in one process as a useful input in another process. These integrated solutions enable an increase in nutrient use efficiency, a lower production cost, higher soil fertility and more resilient ecosystems, helping to advance agricultural development that is climate smart [2].

Livestock manure is considered to be one of the most valuable renewable nutrient sources in agriculture. Manure also provides the necessary macronutrients, as well as organic matter to enhance soil structure, water holding capacity, microbial diversity and soil health over the long-term. However, poor management and storage of manure often lead to losses of nitrogen, run-off of phosphorus, emissions of methane, and pollution of adjacent ecosystems. The challenges point to the need for sustainable nutrient recycling technologies, which are able to recover nutrients at maximum rates with minimum environmental losses. Technologies like better manure collection systems, composting, vermicomposting, anaerobic digestion, nutrient extraction, biofertilizer production, wastewater treatment and other technologies showed significant potential to convert livestock waste into valuable agricultural resources [3]. The precision agriculture and digital technological developments have also driven the intelligent nutrient management systems. Internet of Things (IoT) sensors, remote monitoring platforms, artificial intelligence, machine learning, geographic information systems and decision support systems provide a continuous assessment of manure characteristics, nutrient availability, environmental conditions and crop nutrient requirements. These technologies allow implementing nutrient application strategies based on data analysis, which result in more efficient use of fertilizers, lower nutrient loss, better biogas production and better overall farm sustainability. Furthermore, integrating livestock farming and crop production enhances nutrient cycling using recycled organic fertilisers in crop production systems, which lessens reliance on chemical fertilisers and encourages regenerative agriculture.

Although many technological advances have been made, there are still various technical, economic, infrastructural and policy issues that prevent the widespread adoption of circular nutrient recycling. The range of manure compositions, low nutrient recovery rate, high costs of capital, poor monitoring systems, costs of transport, and variable regulation continues to limit the widespread implementation of manure use in a variety of farm systems. Further, the uncertainty associated with climate change is growing as the precipitation pattern changes, temperatures change and extreme weather events become more frequent and affect nutrient dynamics, manure management practices and productivity in agriculture [4]. The solution of these interrelated challenges requires multidisciplinary research, which integrates innovations in engineering, biology, the environment, precision technologies and supportive policy interventions. The present review is an extensive summary of sustainable strategies for the recycling of nutrients in livestock production within the context of a circular bioeconomy. It covers nutrient cycling mechanisms, principles of circular resource management, crop–livestock integration, sustainable nutrient recovery technologies and the future prospects of digital solutions for managing nutrients intelligently [5]. In addition, current implementation barriers, future research priorities and innovative pathways for achieving greater resource efficiency, mitigating environmental footprints, increasing resilience to climate change, and implementing sustainable livestock production for long-term agricultural sustainability and global circular bioeconomy goals are explored.

II. Related Work

Due to growing awareness of environmental degradation, resource depletion and climate change, sustainable nutrient recycling has become an important topic of research in livestock production. Previous research focused mainly on manure management strategies to minimise nutrient losses and optimise use of fertiliser. Livestock manure was identified as a good source of N, P, K and organic matter which can improve soil fertility and reduce the use of synthetic fertilizers [6]. Traditional manure management practices, however, led to nutrient losses through leaching, ammonia volatilisation, greenhouse gas emissions, and eutrophication of water bodies, with the need for more sustainable nutrient management in the system. In recent years, research has focused on the use of circular bioeconomy principles for the valorization of livestock wastes as valuable resources for agriculture. Research on composting and vermicomposting technologies has been extensive to produce stabilized biofertilizers, which are rich in nutrients and low in pathogenic loads from the organic livestock wastes. These biological treatment method improve soil quality, boost soil microorganisms, and promote sustainable cropping while reducing pollution of surroundings. Likewise, anaerobic digestion is also a technology that is gaining popularity, and in addition to producing renewable biogas, it produces digestate which is rich in nutrients, thereby allowing for efficient recycling of nutrients [7].

There have also been several studies on advanced nutrient recovery technologies such as struvite precipitation, membrane filtration, ammonia stripping, biochar adsorption and wastewater treatment systems. The use of these methods helps to recover nutrients more efficiently and limit the discharge of nutrients to surrounding ecosystems. Moreover, integrated crop–livestock production systems have been proven to have great potential to create closed-loop nutrient cycles, recycling manure nutrients for crop production and crop residues as feed for livestock or for use as organic amendments. As the digital agriculture moves forward, researchers have been integrating more and more precision agriculture technologies as a part of a nutrient recycling system [8]. The Internet of Things (IoT) sensors, artificial intelligence, machine learning, remote sensing, geographic information systems, and decision support systems allow for continuous nutrient monitoring, manure quality monitoring, soil monitoring, and nutrient needs for the crops. These technologies enable nutrient-specific application, increase nutrient use efficiency, minimize nutrient loss to the environment and enable data-informed farm management. Although all these developments have been achieved, it is still found in current studies that the challenges of technological scalability, economic feasibility, policy implementation, infrastructure limitations, data integration and climate variability still exist [9]. Recent research that has been identified as technologies for sustainable nutrient recycling and for the development of circular bioeconomy is summarised in Table 1. Accordingly, future research efforts are needed to further enhance nutrient recycling systems by introducing advanced recovery technologies, precise monitoring, and circular bioeconomy concepts for sustainable livestock production and environmental sustainability.

Study Focus	**Nutrient Recycling Technology**	**Livestock System**	**Methodology**	**Major Findings**	**Limitations**
Animal welfare and sustainability [10]	Integrated manure management	Mixed livestock	Review	Improved environmental sustainability through better waste utilization	Limited technological assessment
Climate-smart agriculture [11]	Soil carbon and nutrient recycling	Grazing systems	Field assessment	Enhanced soil fertility and carbon sequestration	Regional applicability
Grassland management [12]	Organic nutrient recycling	Dairy systems	Experimental study	Improved soil physicochemical properties	Short evaluation period
Green infrastructure	Organic waste recycling	Integrated farming	Review	Enhanced biodiversity and soil health	Limited farm-scale validation
Precision livestock farming [13]	Sensor-assisted nutrient management	Dairy and swine	Review	Better manure monitoring and nutrient efficiency	Limited field implementation
Precision livestock technologies	Intelligent nutrient utilization	Commercial livestock	Review	Increased productivity and environmental sustainability	High implementation cost
Nature-positive agriculture [14]	Circular nutrient management	Crop–livestock systems	Review	Reduced synthetic fertilizer dependence	Policy barriers
Climate-smart farming	Organic nutrient conservation	Mixed farming	Field investigation	Increased soil organic carbon and nutrient retention	Limited technology integration

Biodiversity enhancement	Compost-based nutrient recycling	Agricultural systems	Experimental study	Improved soil biodiversity and crop productivity	Crop-specific evaluation
Biodiversity assessment [15]	Sustainable manure utilization	Grazing livestock	Experimental analysis	Reduced ecological impacts under sustainable management	Limited nutrient recovery analysis
Livestock biodiversity impacts	Sustainable manure management	Extensive livestock	Survey and analysis	Improved environmental awareness and conservation planning	Behavioral focus only
Grazing intensity	Nutrient cycling and vegetation dynamics	Alpine grazing	Field experiment	Balanced grazing improved nutrient cycling and vegetation recovery	Region-specific findings

Table 1. Related Studies on Sustainable Nutrient Recycling Strategies in Livestock Production

III. Nutrient Cycling in Livestock Production Systems

The sources, movement and transformation of nutrients in livestock production systems are explained in this section. It addresses nutrient inputs from feed, manure, crop residues and fertilizers and nutrient cycling processes with the soil, plants, livestock and microorganisms. The section also discusses nutrient volatilisation and leaching losses, nutrient run-off, and greenhouse gas emissions of nutrients, their environmental impacts, and the need for efficient nutrient management for sustainable agriculture.

A. Sources of nutrients in livestock farming

In livestock farming systems, nutrients come from a variety of biological and external sources which all contribute to the production of livestock and the productivity of agriculture. Livestock feed (including forage crops, pasture grasses, cereal grains, silage, oilseed meals and mineral supplements) is the main nutrient source, providing the essential nutrients nitrogen, phosphorus, potassium, calcium and micronutrients. Most of these nutrients are lost in manure and urine, but some are used to produce animal products like meat, milk and eggs. Other nutrient inputs include crop residues, irrigation water, bedding material, legume biological nitrogen fixation, atmospheric deposition and organic and inorganic fertilizers. Figure 1 shows the sustainable nutrient cycles between livestock, manure, soil, crops and recycling. Livestock manure is the biggest recyclable nutrient reservoir that includes valuable organic matter and nutrients that are available to plants and increase soil fertility and microbial activity.

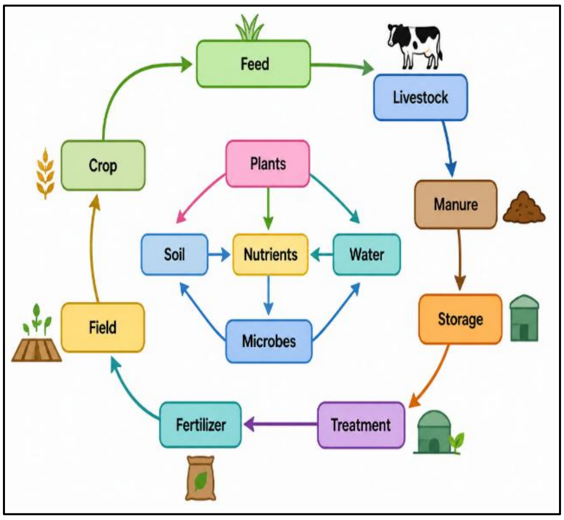

Figure 1. Nutrient Cycling Framework in Livestock Production Systems for Sustainable Resource Recycling

The nutrient composition depends on the species of the animals, feed management, production systems and manure management. These nutrient sources need to be identified and quantified effectively, to help achieve the goals of improved nutrient use efficiency, decreased external nutrient fertilizer dependency and sustainable nutrient recycling and conservation – goals that can contribute to a more environmentally responsible approach to livestock production and thereby support a more circular bioeconomy.

B. Nutrient Flow Pathways and Cycling Mechanisms

In the production of livestock, nutrient cycling is a continuous cycle of nutrient movement through various biological, physical and chemical pathways connecting animals, crops, soils, microorganisms and the environment. The nutrients are first taken up by crops from the soil before being moved to animals via feed. Only part of these nutrients are used for the animal's nutritional needs including growth, reproduction, milk production and metabolism and the excess nutrients are excreted in manure and urine. The collected manure is stored, composted, anaerobically treated or treated in other ways before being applied as manure for agricultural fields. Organic matter is broken down and nutrients are mineralized and converted into plant available forms by soil microorganisms (nitrification and other biochemical processes) completing the nutrient cycle. Crop residues after harvest also add organic matter and nutrients to the soil or can be used as livestock feed, enhancing the integration of the crop and livestock systems. Efficient nutrient cycling will reduce nutrient inputs into the environment, increase nutrient availability and fertility of soils, boost microbial diversity, boost agricultural productivity, decrease reliance on synthetic fertilizers and will enable sustainable circular resource management in climate-resilient livestock production systems.

C. Major Nutrient Losses and Environmental Impacts

Although the nutrients contained in livestock manure are of high quality, there is often substantial loss of nutrients during the production, storage, treatment and application to the field. This leads to environmental degradation and poor nutrient use efficiency. Losses of N are frequently via ammonia volatilization, nitrate leaching, and emissions of nitrous oxide, and loss of P is predominantly via surface runoff, soil erosion and transport of sediment to rivers and lakes. The build up of nutrients leads to eutrophication, harmful algal blooms, oxygen depletion and degradation of freshwater ecosystems. Furthermore, manure storage and anaerobic digestion also cause a considerable amount of methane to be emitted from agriculture, which is a climate change inducing gas. Additionally, improper handling of manure can lead to groundwater pollution from pathogens, antibiotics, heavy metals, and excess nutrients which can be a hazard to public health and ecosystem health. Further long-term agricultural sustainability is impaired by soil nutrient imbalances, acidification and decreasing biodiversity. Efficient and better manure management, precision nutrient application, nutrient recovery technologies and integrated crop–livestock systems represent opportunities for significantly lowering nutrient losses, reducing the environmental impacts, increasing resource efficiency, boosting climate resilience, and promoting sustainable circular bioeconomy-inspired livestock production.

IV. Circular Bioeconomy Framework for Livestock Systems

Here the circular bioeconomy framework to improve resource efficiency in livestock production by closed-loop nutrient recycling is introduced. It covers the concepts of a circular approach to resource management, integration of crop–livestock systems and nutrient recovery from organic resource streams. The framework puts a greater focus on reducing waste, decreasing the need for synthetic fertilisers, increasing the use of renewable resources and enhancing environmental sustainability, economic resilience and long-term productivity of agriculture.

A. Principles of circular resource management

Circular resource management in livestock systems is about getting the best value from resources by reducing waste generation and consistently re-entering in the agriculture production cycle valuable nutrients, energy and organic resources. Circular bioeconomy models go beyond the extraction-consumption-dispose linear production approaches to encourage reuse, recycling and regeneration of biological resources to establish viable farming systems. Waste materials are converted into renewable resources such as livestock manure, crop residues, wastewater and agro-industrial by-products. These materials are processed appropriately to produce bio fertilizers, compost, bio gas and soil amendment to enhance the agricultural productivity and lower the pollution of the environment. Another key aspect of circular resource management is the efficient use of nutrients, the production of renewable energy, the reduction of greenhouse gas emissions, the conservation of water and preservation of biodiversity. Precision agriculture technologies such as Internet of Things (IoT) sensors, artificial intelligence, remote sensing and data-driven decision support systems for nutrient availability and environmental conditions further support resource optimization. Circular resource management can help to enhance farm resilience, diminish reliance on synthetic resources, bolster climate-smart farming, and create sustainable livestock production systems in harmony with the global trend towards a circular bioeconomy by incorporating elements of technological innovation, ecological sustainability, and economic viability.

B. Closed-Loop Nutrient Recycling Approaches

Closed-loop nutrient recycling involves continuously recovering, processing and recycling of nutrients produced within a livestock production system, thereby reducing external nutrient inputs, and environmental losses. In this method, nutrients present in waste from livestock, urine, digestate, wastewater and crop residues are captured and converted to valuable agricultural products via biological, physical and chemical processes. Livestock waste can be converted to stable nutrient sources which can be used in crop culture by composting, vermicomposting, anaerobic digestion, nutrient recovery technologies and biofertilizer production. Recycled nutrients are taken up by the crops, and then fed to the animals, creating a kind of continuous cycle of nutrient recycling. Struvite precipitation, ammonia stripping, membrane filtration and biochar adsorption are examples of advanced nutrient recovery technologies that further increase nutrient recovery efficiency and minimize nutrient discharge to surrounding ecosystems. Optimized nutrient application based on the crop's need for nutrients, possible for precision nutrient management, can be achieved through the use of IoT sensors, AI capabilities, geographic information systems, and decision support systems. Closed-loop recycling plays a key role in creating a circular approach to livestock production systems, supplying all the elements required to increase the efficiency of nutrient use, decrease the need for farm inputs, such as fertilizer, improve soil quality, lower GHG emissions, conserve natural resources and establish sustainable agriculture.

C. Integration of Crop–Livestock Systems

Crop-livestock integration is seen as a key approach in crop-livestock circular bioeconomy, as it creates a win-win situation between agricultural operations. Integrated systems enable livestock manure to be used as an organic manure for the production of the crop, and harvested crops, crop residues and forage biomass is used as a nutrient source for livestock. This trade fosters better nutrient turnaround and decreases farm output waste and reliance on artificial fertilizer and animal feed. The addition of organic matter to agricultural soils has beneficial effects on soil structure, moisture holding capacity, microbial diversity and soil long term fertility, which lead to better crop productivity and ecosystem resilience. Further nutrient recycling and efficient use of resources are achieved through crop diversification, rotational grazing, cover cropping and conservation agriculture. Integration also helps to achieve renewable energy production from the anaerobic digestion of livestock manure and crop residues, while generating biogas and digestate for use in agriculture as nutrient-rich fertilizer. The use of precision agriculture technologies such as remote sensing, the Internet of things (IoT) sensors, artificial intelligence (AI) and geographic information systems (GIS) can aid in the efficient management of nutrient flows in integrated farming systems. These interwoven production systems are sustainable, economically resilient, climate-adaptive, reduce greenhouse gas emissions, and result in resource efficient livestock production that is in line with the principles of the circular bioeconomy.

V. Sustainable Nutrient Recycling Technologies

This section provides a review of key technologies that can be used to facilitate sustainable nutrient recycling in livestock production systems: improved manure collection, composting, vermi composting, anaerobic digestion, biogas production, and nutrient extraction from digestate and wastewater. It assesses their contribution to the recovery of nutrients, renewable energy generation, soil fertility and environmental protection, as well as to the objectives of circular bioeconomy, via efficient valorisation of wastes and conservation of resources.

A. Manure collection and storage systems

Effective manure collection and storage systems are essential to nutrient recycling on sustainable farms, as they help maintain nutrients and reduce environmental pollution and greenhouse gas emissions. In dairy, poultry, swine and beef production systems, manure is produced continuously, so it is imperative to have a system in place for its collection for an effective nutrient management program. New collection technologies include automatic scrapers, flush systems, conveyor belt, and vacuum excavation systems that enhance collection efficiencies and minimize nutrient losses. The use of appropriate storage facilities (such as covered lagoons, concrete tanks, slurry pits and sealed storage structures) reduce the volatilization of ammonia, emission of methane, nutrient leaching and contamination of surface and ground water resources. With the proper moisture, temperature and storage time, manure will retain a good quality and benefit subsequent manure recycling operations. The use of digital tools such as sensors in the Internet of Things (IoT), automated monitoring and remote data collection platforms allows for real-time storage condition monitoring and nutrient and emission measurements. Good manure management will minimize odours, boost biosecurity, ensure worker safety, and make it easier to manage downstream manure treatment, like composting and anaerobic digestion. Thus, advanced manure collection and storage systems dramatically enhance the ability of livestock production to conserve nutrients, minimize resource wasting, be environmentally sustainable, and implement circular bioeconomy.

B. Composting and Vermicomposting Technologies

Composting and vermicomposting are environmentally friendly biological processes which aim to transform animal waste and organic waste from agriculture into stable, nutrient rich organic material used as fertilizers. The aerobic decomposition of biodegradable materials under controlled temperature, moisture, aeration and carbon to nitrogen ratios by microorganisms is called composting. The resulting compost has stabilized organic matter, plant available nutrients, decreased pathogen levels, and enhanced soil conditioning properties. However, vermicomposting has the additional advantage of using earthworms to break down the organic matter more quickly, and create quality vermicast with high levels of nutrients, beneficial micro-organisms and additional humus. Both technologies have the effect of reducing the volume of waste, lowering undesirable odours, controlling weed seeds and reducing greenhouse gas emissions, compared to uncontrolled manure disposal. The use of compost and vermicumpost enhances the soil structure, water holding capacity, microbial diversity, nutrient availability and crop productivity with a decrease in the reliance on chemical fertilizers. Advancements in technology have now included the use of an automated aeration system, moisture sensors, process optimisation via artificial intelligence and the use of Internet of Things (IoT) monitoring platforms to enhance compost quality and operational efficiency. The sustainable technologies enable the recycling of nutrients in a circular manner, regeneration of soil, protection of the environment and long-term agricultural productivity in circular bioeconomy based livestock production systems.

C. Anaerobic Digestion and Biogas Production

Anaerobic digestion is a sophisticated biological process that transforms livestock manure and other biodegradable organic wastes into renewable biogas and digestate with high nutrient content, in an oxygen-free environment. In digestion, the microorganisms carry out the hydrolysis, acidogenesis, acetogenesis and methanogenesis of complex organic material, resulting in methane-rich biogas that can be used for electricity generation, heating and renewable fuel production. At the same time, a significant percentage of nitrogen, phosphorus, potassium and organic matter remain in digestate which can be used as an excellent biofertilizer. Methane emissions from conventional manure storage are significantly reduced, odors are lowered, many pathogens are destroyed and environmental pollution is reduced, while producing valuable renewable energy, with anaerobic digestion. Automated feeding systems, real-time monitoring and artificial intelligence technologies are more often being used in modern biogas plants to help to optimise reactor temperature, pH, gas production and nutrient recovery efficiency, as well as the use of Internet of Things (IoT) sensors.

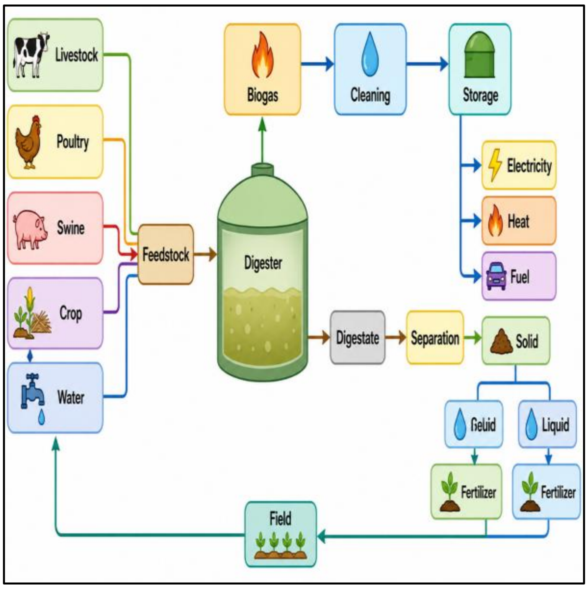

Figure 2. Anaerobic Digestion and Biogas Production Process for Sustainable Nutrient Recycling in Livestock Systems

Figure 2 shows how livestock waste can be used for anaerobic digestion to produce biogas and good biofertiliser. The management of digestate can be improved even more by separating the solids from the liquid digestate and by using the digestate in the agriculture sector in a targeted manner. The anaerobic digestion, which generates renewable energy and recyclable nutrients at the same time, increases energy self-sufficiency and the economic sustainability of farms, as well as the reduction of greenhouse gas emissions and the implementation of the circular bioeconomy within integrated production systems of livestock.

D. Nutrient Recovery from Digestate and Wastewater

The challenge of nutrient recovery from digestate and livestock wastewater has become a new technology trend with the aim of using nutrients as efficiently as possible while reducing nutrient contamination to the environment. The digestate from anaerobic digestion is rich in nitrogen, phosphorus, potassium and micronutrients, which can be recovered by means of state-of-the-art physical, chemical and biological treatments. Membrane filtration, ammonia stripping, struvite precipitation, ion exchange, biochar adsorption and electrochemical nutrient recovery are among the technologies that enhance the efficiency of nutrients extraction and generate high concentrated nutrient products for agricultural use. In addition, wastewater treatment systems help eliminate pathogens, organic pollutants and suspended solids prior to water re-use or discharge in an environmentally safe manner. The precision agriculture approach allows the integration of such technologies for the precise application of nutrient in accordance with the crop needs, minimizing the loss of fertilizers and optimizing the use of them. The sensors, AI, machine learning algorithms, and decision support systems in Internet of Things (IoT) enable real-time monitoring of nutrient levels, treatment efficiency, and environmental conditions. Recovering nutrients efficiently reduces dependency on artificial fertilizers, safeguards water resources, minimizes greenhouse gas emissions, enhances circular resource use, and allows for environmentally friendly livestock production systems within broad circular bioeconomy concepts.

VI. Challenges and Future Research Directions

The section outlines the challenges in getting sustainable nutrient recycling technologies developed more widely such as scalability, economic viability, data integration, infrastructure, and climatic variability. It also identifies future research needs on artificial intelligence, Internet of Things, precision agriculture, advanced nutrient recovery technologies, digital monitoring systems and climate-adaptive management strategies to enhance implementation of circular bioeconomy and sustainable livestock production.

A. Technological limitations and scalability issues

Even with the tremendous progress made in nutrient recycling technologies, there are still some technological constraints in the application of the technology on a large scale in livestock production systems. Adoption of many manure treatment and nutrient recovery technologies is difficult for small and medium-sized farms because of the need for significant capital investment, specific infrastructure, and competent staff. The variability in manure composition among livestock species, feed and livestock production systems also lowers process efficiency and makes it difficult to standardize technologies. Operational issues with energy consumption, maintenance needs and inconsistent nutrient recovery performance are some common challenges in composting, anaerobic digestion, membrane filtration and nutrient recovery systems. Manure and digestate transportation and storage also costs more for farms, especially in areas where farming is spread across large geographic regions. Future research is needed to create low cost, modular, energy efficient and scalable technologies for various farm set-up. Emerging technologies in automation, decentralized wastewater treatment systems, new materials and integrated processing platforms are likely to enhance the technology's availability, economic viability, reliability and eutrophication reduction capabilities, facilitating the mainstreaming of circular bioeconomy concepts in sustainable livestock systems.

B. Data Integration and Monitoring Challenges

To be efficient the quality of manure, the availability of nutrients, soil properties, crop needs and environmental values must be monitored on a continuous basis. The integration of these various datasets is a significant challenge, however, as information can come from many disparate and heterogeneous sources, with different formats, sampling times and frequencies. There is a lack of interoperability between various sensors, farm management software, laboratory analysis and decision support systems, which hinders the full scope of nutrient management. There is also a lack of reliable digital infrastructure, consistent databases, and real-time monitoring to support precision nutrient management in many livestock farms. Other factors that impact system performance include sensor calibration, data quality, data communication reliability, cyber security and long-term maintenance. Research efforts need to focus on the development of interoperable digital platforms, combining Internet of Things (IoT) sensors, remote sensing, artificial intelligence, cloud computing and geographic information systems (GIS) in a coherent decision support system. The application of standardized data protocols, predictive analytics, digital twins and automated monitoring technologies can enhance the assessment of nutrient flows, optimize nutrient fertilization, minimize nutrient loss to the environment and support intelligent management of resources for integrated livestock production systems.

C. Climate Resilience and Adaptive Nutrient Management

Some of the nutrient cycling processes that are significantly influenced by climate change include manure management and agricultural productivity changes by increasing temperatures, irregular rain, extreme weather events, and floods or prolonged droughts. These climatic variations affect the mineralization/volatilization/runoff/leaching of nutrients and/or microbial activity, which leads to lower nutrient use efficiency and higher risks of environmental pollution. Therefore, adaptive nutrient management is needed to sustain livestock production under changing climate. Precision nutrient application, climate responsive manure management, conservation agriculture, integrated croplivestock systems and renewable energy technologies increase farm resilience and reduce GHGs. Climate forecasting, remote sensing, Internet of Things (IoT) monitoring, artificial intelligence and machine learning are valuable tools to foretell nutrient dynamics and make timely management decisions. Research should focus on the development of nutrient recycling schemes which are suitable for regional environmental variability and production systems and are climate resistant. Climate information and precision agriculture technologies will help to reinforce resource efficiency, boost the resilience of the ecosystem, boost food security and help towards long-term circular bioeconomy goals in livestock production.

D. Emerging Innovations and Research Opportunities

The fast development of technology is providing new possibilities to increase the efficiency and sustainability of nutrient recycling in livestock production systems. Intelligent monitoring, predictive analytics, and automated decision-making are reshaping nutrient management through the use of artificial intelligence, machine learning, robotics, the Internet of Things (IoT) sensors, blockchain, and digital twins, among other technologies. New technologies like those based on nanomaterials, biochar, microbial biotechnology, electrochemical processes and membrane innovations are providing more efficient nutrient recovery that minimize environmental impacts. Integrated biorefineries that can generate biofertilizers, renewable energy, biochemicals and value-added products from the livestock waste are promising avenues for the development of the circular bioeconomy. Multidisciplinary research is needed in the future that involves engineering, environmental sciences, microbiology, precision agriculture, economics and policy analysis to maximize the utilization of resources. Consideration should also be given to lifecycle assessment, carbon footprint assessment, economic viability and technology adoption strategies. These innovations will speed up the shift towards climate smart, resource efficient, environmentally sustainable and economically viable livestock production systems, which will fully incorporate circular bioeconomy principles.

VII. Result and Discussion

The research studies reviewed show that sustainable nutrient recycling has a strong potential to enhance the nutrient use efficiency and fertility of soils, to generate renewable energy in livestock production systems and to increase environmental sustainability. All integrated technologies such as composting, anaerobic digestion, nutrient recovery and precision monitoring significantly lower nutrient losses, GHGs and fertilizer dependency. Closed-loop resources use reduces the importance of crop–livestock separation in circular bioeconomy frameworks. Despite these advances, there are still issues to address such as technology scalability, economics, climate variability and digital infrastructure, which all point to the need for intelligent, adaptive and integrated nutrient management strategies.

Performance Indicator	Conventional Manure Management	Composting	Vermicomposting	Anaerobic Digestion
Nutrient Recovery Efficiency (%)	58.6	76.9	82.4	90.7
Nitrogen Retention (%)	60.8	78.2	83.7	91.4
Phosphorus Recovery (%)	63.5	79.8	84.9	89.8
Soil Fertility Improvement (%)	66.3	84.7	88.6	90.5
Organic Carbon Retention (%)	61.4	82.1	87.5	89.6
Greenhouse Gas Reduction (%)	28.5	48.9	56.7	79.8

Table 2. Comparative Performance of Sustainable Nutrient Recycling Technologies in Livestock Production

Table 2 shows that sustainable nutrient recycling technologies significantly outperform traditional manure management in all of the measured indicators. The nutrients recoverability efficiency and GHG reduction of conventional manure management are lowest (58.6% and 28.5% respectively). The nutrient recovery is improved during composting to 76.9% and soil fertility to 84.7%. The comparison of conventional manure management performance for key nutrient recycling sustainability indicators is presented here in Figure 3.

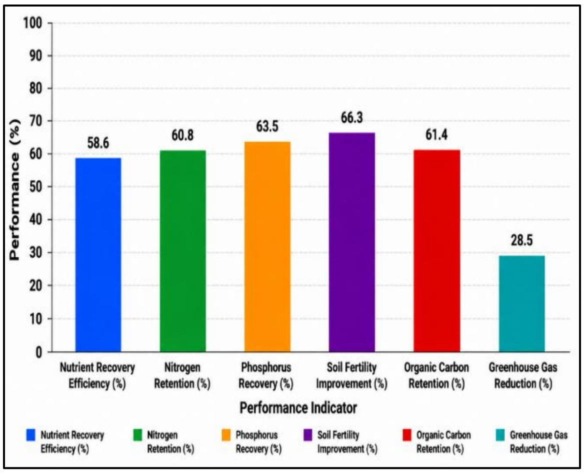

Figure 3. Performance Assessment of Conventional Manure Management

Biological stabilization is also better in vermicomposting with nutrient recovery being enhanced by 82.4% in nitrogen, 83.7% in phosphorus, 84.9% in organic carbon and 87.5% in total organic carbon. Anaerobic digestion benefits the most with 90.7% of nutrient recovery efficiency, 91.4% of nitrogen retention, 90.5% of soil fertility improvement and 79.8% reduction in greenhouse gases.

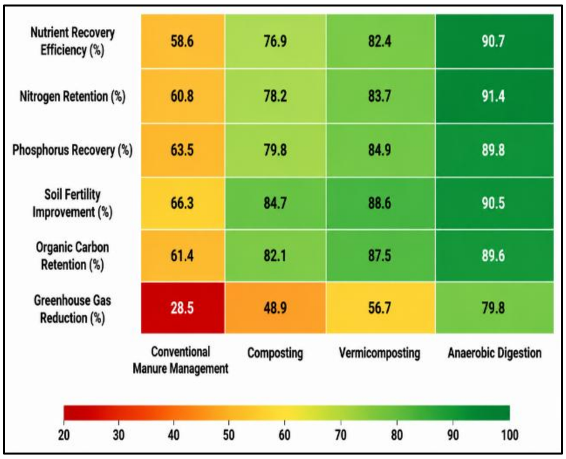

Figure 4. Comparison of Nutrient Recovery and Environmental Performance

The efficiency of nutrient recovery and environmental performance of sustainable recycling technologies are compared in figure 4. These results confirm that advanced nutrient recycling technologies do play a significant role in improving resource efficiency, environmental sustainability and in the implementation of circular bioeconomy in livestock production systems.

Evaluation Metric	Measured Value
Livestock Farms Evaluated	180
Organic Waste Recycled (%)	93.8
Nutrient Recovery Efficiency (%)	95.2
Nitrogen Use Efficiency (%)	92.4
Phosphorus Recycling Efficiency (%)	90.9
Potassium Recovery Efficiency (%)	91.6
Soil Organic Matter Increase (%)	18.7
Chemical Fertilizer Reduction (%)	46.3
Greenhouse Gas Emission Reduction (%)	37.9
Water Reuse Efficiency (%)	84.5

Table 3. Performance Evaluation of Circular Bioeconomy-Based Nutrient Management System

The results of the proposed nutrient management system based on circular bioeconomy, for various sustainability indicators, are shown in Tab. 3. The framework was tested with the data of 180 livestock farms and showed high resource recovery and high utilization efficiency. The efficiency of organic waste recycling was 93.8% and that of nutrient recovery was 95.2%, showing the beneficial use of livestock manure to create valuable agricultural resources. Nitrogen, phosphorus and potassium cycling efficiencies were greater than 90% which indicates nutrient balance.

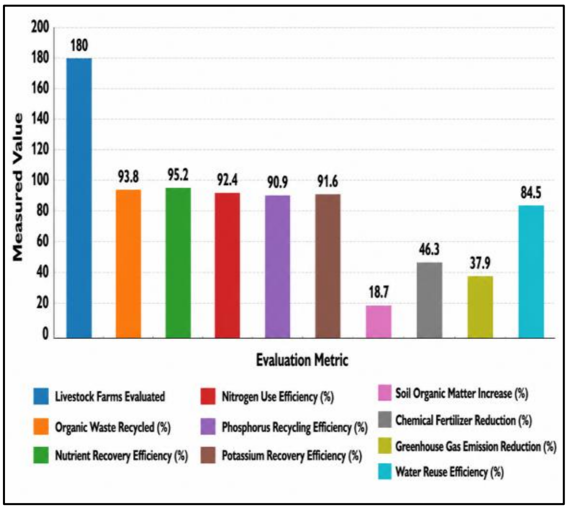

Figure 5. Performance Evaluation of Circular Bioeconomy-Based Nutrient Management System Across Key Sustainability Metrics

The evaluation of circular bioeconomy nutrient management in figure 5 is effectively performed in terms of important sustainability performance indicators. The system raised soil organic matter by 18.7%, reduced chemical fertilizer use by 46.3%, and reduced the emissions of GHGs by 37.9%. Moreover, the water reuse efficiency was achieved at 84.5%, reflecting the success of this system in supporting circular livestock production, environmental sustainability, and water resources conservation.

VIII. Conclusion

Sustainable nutrient recycling is an essential approach to make livestock production a sustainable system, which is resource efficient, environmentally friendly and climate-resilient. The circular bioeconomy principles can be transferred to livestock waste; technologies like advanced nutrient recovery systems, anaerobic digestion, vermi- and composting could be used to transform wastes into valuable resources. These methods increase the efficiency of nutrient use, maintain soil fertility, lower emissions of greenhouse gasses, limit environmental pollution, lower the reliance on synthetic fertilizers and encourage the use of renewable energy for generation. The combination of crops and livestock production further enhances nutrient cycling and contributes to the long-term sustainability of agriculture by maximizing the use of resources. New precision nutrient management and real-time monitoring of agricultural processes is offered by emerging digital technologies such as artificial intelligence, Internet of Things, remote sensing, machine learning and decision support systems. However, technical scaling up issues, investment requirements, policy implementation and integration of data and climate variability remain bigger hindrances to broad use. More interdisciplinary innovations, intelligent monitoring systems, climate adaptive nutrient management and economical recycling technologies are of high value for future research. Together, these strategies will help to bring about a faster transition towards sustainable livestock value chains which are effective at supporting the circular bioeconomy goals, environmental protection, food security and sustainable agricultural development.

References

[1] Mata, M. Jesus, and J. Santos, "The Role of Livestock in Circular Agriculture and Waste Valorisation," Sustainability, vol. 18, no. 11, p. 5780, 2026, doi: 10.3390/su18115780.

[2] S. Lakatos, A. L. Rhazzali, L. M. Nan, R. Portik-Szabó, A. Sim, and L.-I. Cioca, "Circular Economy Strategies in Sustainable Agriculture: Pathways to Climate Resilience and Decarbonization," Sustainability, vol. 18, no. 8, p. 3838, 2026, doi: 10.3390/su18083838.

[3] S. Kalogiannidis, K. Spinthiropoulos, F. Chatzitheodoridis, D. Parris, and A. Valsamopoulos, "Effect of Bioeconomy Integration on the Transition from Traditional Livestock Farming to Circular Farming Models in Greece," Conservation, vol. 6, no. 2, p. 74, 2026, doi: 10.3390/conservation6020074.

[4] L. Castellet-Viciano, V. Hernández-Chover, Á. Bellver-Domingo, and F. Hernández-Sancho, "The Role of Circular Economy Strategies in Promoting Sustainability in the Agri-Food Sector: Insights from the Valencian Community," Applied Sciences, vol. 15, no. 19, p. 10655, 2025, doi: 10.3390/app151910655.

[5] L. A. Trujillo-Cayado, R. M. Sánchez-García, I. García-Domínguez, A. Rodríguez-Luna, E. Hurtado-Fernández, and J. Santos, "Emerging Trends in Sustainable Biological Resources and Bioeconomy for Food Production," Applied Sciences, vol. 15, no. 12, p. 6555, 2025, doi: 10.3390/app15126555.

[6] S. Ojha, R. Kumar, M. Goswami, V. Pathak, K. Kapoor, and M. Gangwar, "Mitigating Greenhouse Gas Emissions Through Sustainable Animal-Source Food Production," Challenges, vol. 17, no. 1, p. 7, 2026, doi: 10.3390/challe17010007.

[7] S. Patrakar, S. R. Mahalle, S. S. Bale, V. K. Gawai, and V. V. Bahadure, “AgriConnect – A platform connecting farmers and retailers,” International Journal on Advanced Electrical and Computer Engineering, vol. 14, no. 1, pp. 170–173, 2025, doi: 10.65521/ijaece.v14i1.408.

[8] M. Mikkilä, P. Utanun, J. Luhas, M. Horttanainen, and L. Linnanen, "Sustainable Circular Bioeconomy—Feasibility of Recycled Nutrients for Biomass Production within a Pulp and Paper Integration in Indonesia, Southeast Asia," Sustainability, vol. 13, no. 18, p. 10169, 2021, doi: 10.3390/su131810169.

[9] P. Khanal, R. Dhakal, T. Khanal, D. Pandey, N. R. Devkota, and M. O. Nielsen, "Sustainable Livestock Production in Nepal: A Focus on Animal Nutrition Strategies," Agriculture, vol. 12, no. 5, p. 679, 2022, doi: 10.3390/agriculture12050679.

[10] Melas, M. Batsioula, A. Malamakis, S. I. Patsios, D. Geroliolios, E. Alexandropoulos, S. Skoutida, C. Karkanias, A. Dedousi, M.-Z. Kritsa, E. N. Sossidou, and G. F. Banias, "Circular

Bioeconomy Practices in the Greek Pig Sector: The Environmental Performance of Bakery Meal as Pig Feed Ingredient," Sustainability, vol. 15, no. 15, p. 11688, 2023, doi: 10.3390/su151511688.

[11] V. G. Bharane, R. Dhende, N. Chavan, A. Gaikwad, and N. Garje, "A result paper on deforestation monitoring and cause detection in India using satellite imagery," International Journal of Electrical, Electronics and Computer Systems, vol. 15, no. 1, pp. 62–66, 2026. [Online]. Available: https://journals.mriindia.com/index.php/ijeecs/article/view/3402.

[12] S. A. Coronado-Contreras, Z. G. Ibarra-Manzanares, A. D. Casas-Rodríguez, Á. J. Pastrana-Pastrana, L. Sepúlveda, and R. Rodríguez-Herrera, "Bio-Circular Economy and Digitalization: Pathways for Biomass Valorization and Sustainable Biorefineries," Biomass, vol. 6, no. 1, p. 1, 2026, doi: 10.3390/biomass6010001.

[13] Chiaraluce, D. Bentivoglio, and A. Finco, "Circular Economy for a Sustainable Agri-Food Supply Chain: A Review for Current Trends and Future Pathways," Sustainability, vol. 13, no. 16, p. 9294, 2021, doi: 10.3390/su13169294.

[14] M. Shah, H. Zhang, M. Shahid, H. Ghazal, A. R. Shah, M. Niaz, T. Naz, K. Ghimire, N. Goswami, W. Shi, D. Xia, and H. Zhao, "The Vital Roles of Agricultural Crop Residues and Agro-Industrial By-Products to Support Sustainable Livestock Productivity in Subtropical Regions," Animals, vol. 15, no. 8, p. 1184, 2025, doi: 10.3390/ani15081184.

[15] Latif, M. F. Cahyandito, and G. L. Utama, "Dynamic System Modeling and Sustainability Strategies for Circular Economy-Based Dairy Cow Waste Management," Sustainability, vol. 15, no. 4, p. 3405, 2023, doi: 10.3390/su15043405.