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The Role of Bovines in Sustainable and Circular Agriculture Systems

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Sustainable agriculture aims to increase food production while reducing environmental impacts by integrating ecological and biological processes. However, its broad and often unclear definition highlights the need for well-defined frameworks to guide its application. Circular agriculture builds on this concept by promoting closed-loop systems that enhance resource efficiency and minimize waste, converting agricultural outputs into valuable inputs. A key element of this approach is the role of microorganisms in nutrient cycling, along with the integration of crop and livestock systems, which together improve biomass production, soil health and nutrient use efficiency. In traditional farming systems, especially in regions such as India and Sub-Saharan Africa, livestock are central to agricultural sustainability. They contribute through manure recycling, draught power and the conversion of crop residues into valuable products. Indigenous knowledge systems further support sustainability by encouraging the use of biofertilizers, enhancing microbial activity and promoting climate-resilient practices. Integrated farming systems not only increase farm income and employment opportunities but also strengthen climate-smart agriculture by improving soil fertility, water-use efficiency and reducing greenhouse gas emissions. Despite these benefits, several challenges limit widespread adoption, including competition for resources, high labor requirements, environmental trade-offs and insufficient policy support. Nevertheless, improved livestock management strategies—such as precision feeding, efficient manure management and genetic improvements—offer strong potential to reduce greenhouse gas emissions. Ultimately, advancing circular and integrated agricultural systems will depend on coordinated technological innovation, supportive policies and greater awareness among stakeholders to achieve sustainable, resilient, and food-secure farming systems.

Introduction

Sustainable agriculture focuses on technologies and practices that do not have adverse effects on environmental goods and services, are accessible to and effective for farmers and lead to improvements in food productivity. It integrates biological and ecological processes into food production while minimizing harmful non-renewable inputs (J. Pretty *et al.*, 2008). However, the concept remains very vague and ambiguous in its meaning, requiring frameworks for understanding its components (Sarah Velten *et al.*, 2015). Circular agriculture builds upon these ideas by involving closed-loop systems and controlled environment agriculture, emphasizing microbial techniques for regional food production. It goes beyond manure management and requires adaptation of both food production and consumption patterns, matching local capacity to produce with food demand (A. Schut *et al.*, 2021). Microorganisms serve as linchpins connecting plant and animal agriculture through complex cycles involving carbon, nitrogen, phosphate, and additional micronutrients (Till Glockow *et* *al.*, 2024). Integration of plant and animal resources to achieve optimal biomass output within a given ecological and socioeconomic setting should be the ultimate goal for sustainable farming systems (C. F. Parker *et al.,* 1990). In Sub-Saharan Africa, the integration of livestock into farming systems is important for sustainable agriculture as the recycling of nutrients for crop production through returns of animal manure is a central element. Better integration of crop and livestock systems offers great potential to rebalance the economic and environmental trade-offs. Herbivorous livestock provide multiple benefits, including improving food and nutrition security, increased recycling of organic matter and nutrients, and the associated soil fertility amendments, as well as adding value to crop residues by turning them into nutrient-rich foods (A. Ayantunde *et al.*, 2018). One of the most important biological relationships in the world is that between herbivores and forages. Integrated systems with livestock demonstrate four times more biomass than monoculture systems and achieve a 0.99 Nitrogen Recycling Index compared with 0.38 in non-integrated systems (Arnulfo Domínguez-Hernández *et al.*, 2025).

Understanding Circular Agriculture

Circular economy principles applied to agriculture represent a transition from linear “take-make-use-dispose” systems to regenerative “grow-make-use-restore” models that prioritize resource efficiency and waste elimination (J. F. Velasco-Muñoz *et al.*, 2021). In this context, the circular economy framework has been adapted to suit agricultural sector requirements, providing a comprehensive definition and field-specific principles. At its core, this framework emphasizes the development of closed-loop systems in which materials and resources are continuously reused instead of discarded (Efthymios C. Rodias *et al.*, 2020). Within this framework, waste minimization and resource maximization are achieved through integrated and interdependent strategies that convert agricultural byproducts into valuable inputs. Practices such as composting, crop rotation, agroforestry and integrated pest management contribute to the establishment of zero-waste systems by enabling reuse of agricultural residues, recycling of water and use of renewable energy (Kiran Kotyal *et al.*, 2023). These approaches are further strengthened by technological innovations, including anaerobic digestion and biomass conversion, which play a critical role in advancing sustainability applications (Jing Peng *et al.*, 2025). Additionally, the generation of bioenergy from agricultural waste particularly through biogas for electricity and biofuel production offers a promising pathway for reinforcing circular practices (M. V. Barros *et al.*, 2020).

A key component of circular agriculture is the optimization of nutrient cycling and energy flows within agro-ecosystems through the integration of biological and technological processes. The water-energy-nutrient nexus framework supports reduced natural resource consumption, decreased reliance on chemical fertilizers, utilization of bio-based materials derived from agricultural and livestock residues and the reuse of wastewater from agrifood systems (Efthymios C. Rodias *et al.*, 2020). Advancements in eco-innovative technologies, such as constructed wetlands and algae-based systems, further enhance nutrient recovery and contribute to greenhouse gas emission reduction (K. Praveen *et al.*, 2024). The use of recycled nutrient fertilizers also promotes efficiency and waste reduction, although concerns regarding contaminants such as toxic elements and microplastics remain significant challenges (Cheryl Marie Cordeiro *et al.*, 2024).

Mixed farming systems represent a practical and effective application of circular economy principles by integrating crop and livestock production into cohesive resource cycles. These systems utilize crop residues as livestock feed, incorporate residues into soil to improve fertility, apply manure as a natural fertilizer and develop dual-purpose crops that support both agricultural and livestock productivity. Such approaches reflect a long-standing tradition of circular resource use efficiency. Additional innovations include transforming cereal straw into high-quality feed, using cassava waste as livestock feed and incorporating insects as alternative feed sources (A. J. Duncan *et al.*, 2023). Furthermore, circular practices can optimize resource-intensive stages such as field preparation, fertilization and irrigation, while converting waste generated from activities like pruning and mulching into productive inputs. Despite its potential, the implementation of circular economy principles in agriculture faces several interconnected challenges. Effective waste and wastewater management requires the adoption of advanced environmental technologies and coordinated global efforts to address climate change and biodiversity loss (Ioana-Maria Toplicean *et al.*, 2024). Current research is predominantly focused on environmental dimensions, highlighting the need to further develop economic and social aspects of circular agriculture (J. F. Velasco-Muñoz *et al.*, 2022). Achieving successful implementation depends on continued technological innovation, effective management of contaminants, supportive policy frameworks, appropriate market incentives and increased awareness among stakeholders regarding the benefits and safety of circular practices.

Bovines in Traditional Farming Systems

Cattle and buffalo have historically occupied a central role in Indian agriculture, where livestock are deeply integrated into cultural and religious practices that influence economic activities, traditions, festivals and social structures (V.S. Dhole *et al.*, 2025). Indigenous cattle breeds contribute significantly to rural livelihoods by providing milk, meat, manure and draught power, while also possessing strong cultural and religious importance. These breeds exhibit rich genetic diversity and resilience to tropical diseases and harsh climatic conditions, making them particularly valuable in local farming systems (Sukanya.P *et al*., 2025). This close human–livestock relationship is further reflected in traditional practices such as Bail Pola, cattle fairs and folk traditions, which symbolize the reverence farmers have for their animals. Building on this cultural and ecological foundation, indigenous technical knowledge systems have evolved sophisticated methods for integrating livestock into agricultural processes. Indigenous cattle are often described as “bio-reactors” because they produce dung and urine rich in microbial populations that play a crucial role in activating soil nutrients and supporting crop health. Traditional formulations such as Beejamrut, Jivamrut and Panchagavya are widely used biofertilizers that enhance microbial activity, improve nutrient cycling and strengthen plant immunity. Notably, dung from indigenous cattle contains higher levels of beneficial microorganisms, including bacteria, fungi and actinomycetes, compared to exotic breeds, making it more effective for natural farming applications (Phalguni N Khadse *et al.*, 2026).

These traditional practices are closely linked with integrated crop-livestock farming systems, which provide multiple economic and ecological benefits, particularly in developing countries such as India. Such systems support food security, income generation and employment while enhancing soil fertility and overall farm productivity (Udhaya Nandhini *et al.*, 2018). They also improve water productivity compared to crop-only systems, enable efficient utilization of family labor and reduce economic risks by diversifying farm enterprises (I. Wright *et al.*, 2012). A key feature of these systems is resource recycling, where the waste outputs of one component become inputs for another; for example, manure improves soil fertility and crop yields, while crop residues and by-products serve as livestock feed, addressing feed shortages and improving animal productivity (V. Gupta *et al.*, 2012). Empirical evidence highlights the strong economic potential of integrated farming systems, showing that well-designed models can increase net farm income by two to four times, generate an additional 250–450 man-days of employment per hectare annually and fulfill 30–60% of crop nutrient requirements through internal resource recycling (A. K. Gautam *et al.*, 2025). Livestock play a multifaceted role in natural resource-based livelihood systems and crop-livestock integration has been instrumental in linking agricultural advancements such as the Green and White Revolutions, thereby contributing to rural development (V. Singh *et al.*, 2010).

In addition to economic benefits, these systems contribute significantly to climate-smart agriculture by reducing yield variability, enhancing soil organic carbon stocks, improving water-use efficiency and lowering greenhouse gas emission intensity per unit of agricultural output (A. K. Gautam *et al.*, 2025). Indigenous knowledge systems further strengthen sustainability and resilience through practices such as green manuring, vermicomposting and ethnoveterinary treatments, which promote ecological balance and long-term agricultural stability (Bikram Barman *et al.*, 2024). However, the adoption and scaling of integrated crop-livestock systems face several constraints, including competition for biomass resources, high labor requirements, scarcity of fodder and water, risks related to animal health, and weak market linkages. Furthermore, many indigenous livestock breeds have declined due to reduced profitability and increasing reliance on mechanized agriculture. This trend underscores the urgent need to preserve livestock-based traditional knowledge and cultural heritage while promoting sustainable intensification strategies that enhance both productivity and resilience (Sukanya.P *et al*., 2025).

Sustainable Management Practices

Livestock production systems contribute substantially to greenhouse gas emissions, particularly methane from ruminants, necessitating comprehensive mitigation strategies across multiple intervention points. Feeding interventions represent a primary mitigation avenue, with dietary modifications showing significant emission reduction potential. Improvements in forage digestibility and the inclusion of specialized additives such as tannins, algae and compounds like 3-nitrooxypropanol effectively reduce ruminal methane production (T. Zanon *et al.*, 2025). Dietary lipids, nitrates, and ionophores are identified as among the most effective feed supplements for lowering enteric emissions (P. Gerber *et al*., 2013). Crude protein reduction strategies demonstrate particularly strong outcomes, where an 8% reduction increases nitrogen utilization efficiency by 54% while reducing costs by 11%. Precision feeding technologies further enhance efficiency by enabling daily diet tailoring, reducing nitrogen excretion by 30% compared to conventional group phase feeding (C. Pomar *et al*., 2021).

Manure management across the production chain also offers substantial mitigation opportunities. During animal housing, frequent manure removal, conducted two to three times weekly, effectively reduces greenhouse gas and air pollutant emissions. Storage and treatment interventions demonstrate high efficacy; for example, acidification reduces ammonia emissions by 33–93% and methane by 67–87%, while the use of acids such as lactic acid reduces nitrous oxide emissions by approximately 90% (Xiaojie Yan *et al.*, 2024). A meta-analysis of 126 studies highlights the effectiveness of storage covers, with artificial films achieving 98% ammonia reduction and straw covers achieving 78% reduction (Y. Hou *et al.*, 2015). Anaerobic digestion provides dual benefits by generating renewable energy while simultaneously reducing methane emissions from stored slurry (H. V. D. Meer *et al.*, 2008). Application techniques also vary in effectiveness; shallow injection reduces ammonia emissions by 62–70% but may increase nitrous oxide emissions, illustrating important trade-offs that require careful evaluation.

Advancements in measurement technologies support precise monitoring and facilitate genetic selection strategies. Direct measurement methods and mid-infrared spectroscopy predictions for methane emissions are increasingly being integrated into breeding goals in countries such as Canada. Genetic improvement provides permanent and cumulative benefits through improved productivity and efficiency, reduced system wastage, and direct selection for lower emissions when measurable. Selection for traits such as residual feed intake and longevity enhances system efficiency and contributes to lower overall emissions (Eileen Wall *et al.,* 2010). Increasing animal productivity through planned cross-breeding, optimized nutrition, and improved reproductive efficiency is an effective strategy for reducing greenhouse gas emissions per unit of livestock product (A. Hristov *et al.*, 2013).

The integration of multiple mitigation approaches yields cumulative benefits but requires careful optimization to avoid unintended consequences. Strategies such as lowering dietary crude protein content and acidifying slurry consistently reduce both ammonia and greenhouse gas emissions throughout the manure management chain. However, certain practices introduce trade-offs; for instance, straw-covered slurry storage can increase nitrous oxide emissions significantly, emphasizing the need for whole-system assessment (Y. Hou *et al*., 2015). Combined approaches, such as precision feeding alongside low-protein diets, can achieve nitrogen utilization efficiencies of up to 61%. Effective implementation depends on balancing mitigation efficiency with technical feasibility, economic viability, local regulations, climate conditions and scalability. Overall, integrating breeding, feeding and manure management strategies, supported by strong research and policy incentives, is essential for reducing dairy methane emissions while ensuring sustainable livestock production.

Conclusion

Sustainable and circular agriculture offer vital pathways for reshaping modern food systems into models that are resilient, resource-efficient, and environmentally sustainable. A key element of this transformation is the integration of crop and livestock systems, which supports effective nutrient recycling, enhances soil fertility, increases biomass productivity and improves farm profitability. Traditional agricultural practices, particularly those rooted in indigenous livestock management and local knowledge, provide important examples of ecologically balanced and sustainable farming approaches. Circular agriculture reinforces these systems by encouraging closed-loop resource use, reducing waste and applying innovative technologies such as anaerobic digestion, nutrient recovery, and bio-based inputs. The use of microorganisms and eco-friendly technologies further improves nutrient cycling and decreases reliance on chemical fertilizers, supporting long-term sustainability. In addition, improved livestock management practices—including optimized feeding, efficient manure handling, and genetic improvement—play a significant role in lowering greenhouse gas emissions while enhancing overall productivity.

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