W1375

Circular Bioeconomy and Precision Agriculture/Precision Livestock Farming: Paths Toward a Common Good

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Natural resources are the backbone of the food system, and the resulting production of biomass is pivotal to the development of a circular bioeconomy sector that enables the transition from fossil fuels to renewable energy (Muscat et al., 2021). As the global human population continues to grow, the demand for biomass (i.e., plants, animals) increases. Even so, current levels of biomass harvesting are associated with a variety of environmental issues such as land use, biodiversity loss and climate change (Krausmann et al., 2013), which are exacerbated by population growth. As economies shift to become more bio-based, demands will increase for bio-based products such as bioplastics, bio-lubricants and biochemicals (Scarlat et al., 2015). If these trends remain unchanged, it will become increasingly difficult to meet growing demands without increasing pressure on water, land and other natural resources (Muscat et al., 2020). To prevent further exceeding planetary boundaries, there is widespread acknowledgement of the need to transform our economy, including our food system in terms of production, consumption and waste generation (Steffen et al., 2015; Richardson et al., 2023).

The current linear food system production model of “take-produce-consume-discard” is no longer sustainable. The circular economic model focuses increased attention on the environment by regenerating and reusing materials and products. The circular bioeconomy represents a transformative approach to sustainability by fostering the efficient use, reuse and regeneration of renewable biomass (i.e., animals, plants, microorganisms and their derived products) (McAllister et al., 2025a). Implementing a circular bioeconomy can offer solutions to address global challenges such as resource depletion, biodiversity loss, waste management and environmental impacts, including climate change (McAllister et al., 2025a). There is broad consensus that a critical shift towards a more sustainable food system is urgently needed (Poponi et al., 2022). Even so, transitioning towards a circular food system will require profound systemic changes not only in infrastructure, technology and food production but also in citizen food-related behaviors (Jaeger-Erben et al., 2021).

Meanwhile, new technologies like precision agriculture (PA) and precision livestock farming (PLF) are critical tools that will play a vital role in reaching the common good of a circular bioeconomy. Livestock are a key commodity for human well-being (Herrero et al., 2009). Their importance in providing food, incomes, employment, nutrients and risk insurance to mankind is widely recognized (Perry and Sones, 2007; Thornton et al., 2006). Precision livestock farming uses advanced technologies like sensors, cameras and software to monitor and manage livestock on an individual basis to improve health, welfare and productivity while reducing the environmental impact.

Similarly, PA combines data from soil tests, remote sensing and historical yield records to create nutrient management plans tailored to specific field zones (Pratyusha et al., 2023). Moreover, PA enhances environmental sustainability by mitigating the negative impacts of conventional farming practices (Balafoutis et al., 2017). Applying nutrients only where, when and in the amount needed minimizes nutrient runoff into waterways, which can cause algal blooms and other ecological problems (Wurtsbaugh et al., 2019). In addition, PA reduces greenhouse gas (GHG) emissions associated with fertilizer production and application. Advanced monitoring and feedback systems enable ongoing enhancement of nutrient management strategies, allowing farmers to adjust their practices using real-time data and historical trends (Hedley, 2015). This approach ensures nutrient management is both cost-effective and ecofriendly, supporting the sustainability of agricultural ecosystems (Getahun et al., 2024).

In this paper, we consider several factors that will play major roles in reaching a circular bioeconomy including 1) addressing food waste, 2) the importance of livestock, 3) indigenous chicken farming and 4) the role of PA/PLF on a global playing field that is far from level.

Addressing Food Waste

Food waste valorization has emerged as a critical strategy for sustainable development, addressing both environmental and economic challenges. The global food waste crisis contributes significantly to GHG emissions and, as a result, innovative approaches to converting this waste into valuable products have gained momentum (Pal et al., 2024). Recent research highlights various advanced valorization techniques, such as the conversion of food waste into engineered biochars for CO2 capture, which not only reduces environmental impact but also supports a circular bioeconomy (Economou et al., 2024). In addition, comprehensive reviews emphasize the potential of integrated biorefinery strategies to maximize the recovery of bioactive compounds and bioenergy from food waste, thereby turning waste into wealth and contributing to the United Nations' Sustainable Development Goals (SDGs) (Tamasiga et al., 2022). The current linear model of "take-make-dispose," which has dominated industrial practices for centuries, is increasingly recognized as unsustainable (Pal et al., 2024). In contrast, a circular bioeconomy seeks to create a closed-loop system where waste is minimized, and resources are continuously reused or recycled (Lai et al., 2022).

In agricultural production, food waste begins in the field, where crops may be left unharvested or discarded due to adverse weather conditions, pest infestations, diseases and market fluctuations (Tsegaye et al., 2021). Aesthetic standards set by retailers can lead to rejection of produce that does not meet specific criteria, resulting in food being discarded that is still nutritious and safe to eat (European Commission, 2024). The overemphasized focus on visual perfection leads to the rejection of perfectly edible but cosmetically imperfect products, exacerbating waste (Mohajeri et al., 2021). In sub-Saharan Africa, the absence of proper storage and transportation infrastructure results in substantial losses of fruits and vegetables with some studies indicating that up to 50 percent of produce can be lost before reaching the market (Lee et al., 2023). Additionally, cultural factors and lifestyle choices, such as a preference for variety and the convenience of ready-to-eat meals, can contribute to higher levels of food waste (Duḿee, 2022).

The greatest pressing scientific, economic, social and ethical need facing humanity is protecting the planet for future generations (Toplicean and Datcu, 2024). However, according to the planetary limits concept proposed by Rockström et al. (2009), mankind has already passed the boundaries for a safe operating area in three of the nine major planetary systems, namely climate change, the nitrogen cycle and biodiversity loss (Toplicean and Datcu, 2024). The population has more than tripled (Worldometer, 2025) in the last 50 years, and such expansion can only be supported by an efficient worldwide food production system and, more importantly, by eliminating food waste. Food wastage accounts for the loss of around 1.4 billion tons of crops each year (Toplicean and Datcu, 2024). This is equivalent to 30 percent of all food production for human use and 81 percent of world GHG emissions connected with wasted food (Fesenfeld et al., 2022). Food protein waste, being its most highly valued sector, has a significant impact on the total issue. Intense animal protein production has a direct influence on climate change, accounting for 12 percent of all GHG emissions and 30 percent of all human-induced terrestrial biodiversity loss (Henchion et al., 2017).

The Earth generates about 4.4 billion tons of food annually, which is sufficient to meet the needs of the estimated human population (Toplicean and Datcu, 2024). However, over 1.4 billion tons of food are wasted before it is consumed (Adelodun et al., 2021). According to Xue and Liu (2019), the following are the most prevalent causes of food waste: 1) overcooking; 2) inadequate buying management; 3) keeping food in less-than-ideal circumstances; 4) misinterpreting the use-by and best-before dates; and 5) overstocking. Agricultural losses and waste are more common in low-income nations than in nations with a moderate to high income due to limitations in advanced infrastructure and technologies for harvesting (Wunderlich and Martinez, 2018).

The integration of food waste into the circular bioeconomy offers multiple environmental, economic and social benefits (Pal et al., 2024). Environmentally, it helps mitigate climate change by reducing GHG emissions associated with food waste decomposition in landfills. Economically, it creates new value chains and market opportunities, particularly for local communities and industries. Socially, it contributes to food security by enabling the recovery of nutrients and other valuable components from food waste, which can be reintegrated into the food supply chain. Challenges must be addressed, however, before the benefits of transforming food waste into renewable food resources can be fully realized. One primary challenge is the scalability of food waste valorization processes. While numerous small-scale pilot projects have shown much potential, large-scale application needs additional research and development. Development of innovative technologies and processes that can enhance the conversion of food waste into high-value products is another much needed research area. Finally, using food waste in precision agriculture, where food waste nutrients can be utilized to improve soil health and crop yields, is another area in need of additional research.

Importance of Livestock to a Circular Bioeconomy

A circular bioeconomy is at the intersection between the bioeconomy and the circular economy, with special emphasis on the sustainable use of biomass through closed-loop systems that rely on reducing, reusing and recycling biomass (Fig. 1). It aims to support sustainable well-being for society at large, based on healthy, biodiverse and resilient ecosystems (Palahi et al., 2020). Therefore, the circular bioeconomy provides ecosystem services that allow sustainable production, use, conservation and regeneration of biomass and their transformation into food, feed, fiber, fuel and other materials within ecosystem boundaries (McAllister et al., 2025a).

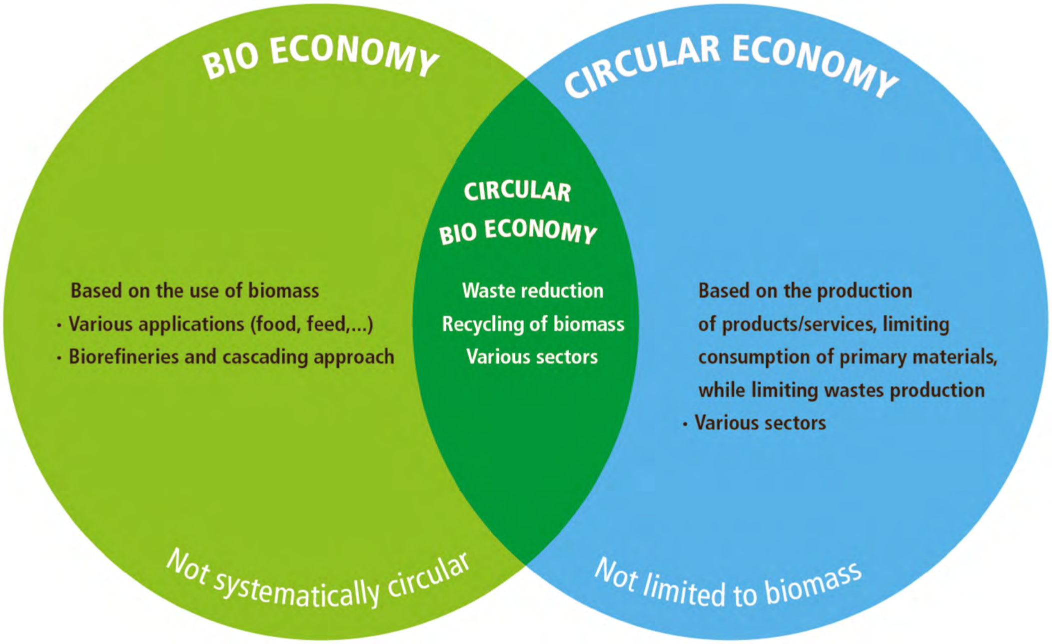

Figure 1: *Bioeconomy and circular economy frameworks and their integration into circular bioeconomy. Source: McAllister et al., 2025a.*

Achieving circularity in the food system implies searching for practices and technologies that minimize the input of finite resources (e.g., fossil fuels and fertilizers, land, water), encourage the use of regenerative practices, and stimulate reuse/recycling of residual streams (e.g., livestock manure) in a manner that adds the highest value to unavoidable food system residues (Ghisellini et al., 2014; Jurgilevich et al., 2016; Corona et al, 2019; Valls-Val et al., 2023).

McAllister et al. (2025b) propose that circularity can also contribute to the goal of achieving net-zero GHG emissions from agriculture. Although, such a lofty goal will demand strenuous response measures in many sectors, including agriculture, a prominent emitter of GHGs, in particular methane and nitrous oxide. Even with the employment of circularity principles, achieving the net-zero target sooner rather than later seems highly improbable, but it can serve a vital role in motivating a fundamental restructuring and reorientation of farming practices, a transition to more precision agriculture and precision livestock farming practices that may also advance ecological and social goals. Examples of such targeted restorative practices may include returning marginal lands to natural vegetation, developing multifunctional landscapes, perennializing farming, reestablishing animal-crop symbioses, resolving the nitrogen enigma, adopting holistic perspectives and rethinking economic rewards (McAllister et al., 2025a) (Fig. 2).

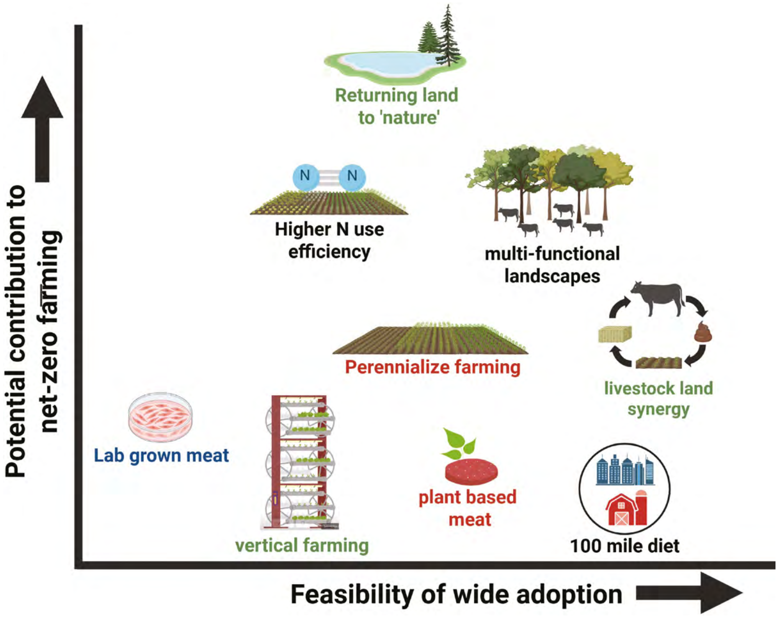

Figure 2: *Examples of agricultural strategies that have been proposed for climate mitigation. Source: McAllister et al. 2025b).*

Implementing circularity in livestock systems should also consider the accessibility and ability to adopt the practice as well as its implications for animal health and well-being (Puente-Rodríguez et al., 2022). Effective implementation of a circular bioeconomy for livestock must also account for multiple ancillary sectors and value/supply chain components, such as transportation, packaging and storage, but the primary determinants of circularity are linked to feed utilization, manure management and the utilization of livestock products (McAllister et al., 2025a).

Livestock currently use about 70 percent of all agricultural land either directly (grazing) or indirectly (concentrated livestock operations; growing livestock feed) (Sakadevan and Nguyen, 2017). And like numerous other human-generated factors, livestock play a role in GHG emissions from the food system (Gerber et al., 2013; Steinfeld et al., 2006). About 40 percent of arable land is used to produce feed (Mottet et al., 2017). No matter how efficiently animal source food is produced, using arable land to produce animal source food production is less efficient than using it directly for plant source food production (Foley et al., 2011; Godfray et al., 2010). Globally, monogastric animals (e.g., pigs and poultry) consume on average about two kg of human-edible feed protein to produce one kg of edible protein (Mottet et al., 2017) and, as a result, they consume more human-edible protein than they produce. There are trade-offs, however, that increase the value of animal production. There are nutrients (vitamins, heme iron, calcium, omega-3 fatty acids, zinc) found in animal-based protein that can be locally difficult to obtain in adequate quantities from plant-source foods alone (Randolph et al., 2007; Murphy and Allen, 2003). Also, animal-based protein offers a better balance of essential amino acids compared to plant sources.

In addition, livestock play a critical role in the circular bioeconomy by recycling resources that are not part of the primary food basket. Livestock are also essential to the sustainability of integrated crop-livestock systems, where the inclusion of forages in rotational cropping systems and the provision of manure contribute to carbon sequestration and soil health (Giacometti et al., 2021). Therefore, livestock play an important role in the circular bioeconomy, as they enable the upcycling of agricultural products that cannot be consumed by humans into valuable nutritional animal-sourced foods, and they produce manure as a fertilizer byproduct (Eisler et al., 2014).

By utilizing nonedible biomass such as grasslands, crop residues, crops designated unsuitable for human food and byproducts from other industries (e.g., oilseed meals, DDGS), livestock can convert low-value resources into high-quality nutrient sources for humans (Tedeschi et al., 2015). In fact, animal-sourced foods provide a significant portion of the world's food supply, including 34 to 40 percent of global protein consumption as well as the provision of vital micronutrients, which are more difficult to obtain from plant-based foods alone (FAO, 2023; Smith et al., 2024). Of the feed consumed by livestock, 86 percent is estimated to be unsuitable as food for humans, with the remaining 14 percent corresponding to one-third of global cereal production (Mottet et al., 2017).

Livestock also produce manure, a valuable organic fertilizer rich in macro- and micro-nutrients and organic matter. Returning manure to the land is one of the oldest examples of a circular bioeconomy. Although, the specialization and geographic concentration of livestock production since the second half of the 20th century has resulted in the spatial decoupling of crop and animal production and limited the opportunities for the utilization of nutrients in animal manure (Naylor et al., 2005).

Areas with high animal density produce excess volumes of nutrients in relation to local capacity of land to absorb this load. As a result, manure nutrients are often not utilized efficiently. In contrast to the nutrient oversupply in some parts of the world (North America, Europe, South and East Asia), there remain vast areas, notably in Africa and Latin America, where harvesting without external nutrient inputs has led to land degradation and depletion of soil fertility (Smaling et al., 1997; Sanchez, 2002). Coupling crop and animal production at an adequate stocking density, together with appropriate management of animal manure as a nutrient source for crops, contributes to agricultural sustainability and reduces the need for synthetic fertilizers (Soussana and Lemaire, 2014).

Livestock can recycle and upcycle resources while playing an important role in feeding humanity by consuming low opportunity cost byproducts and biomass from grasslands (Varijalshapanicker et al., 2019). The available biomass to feed livestock includes crop residues, co-products arising from other industrial processing of plant-based products and animal-based products or from other industrial processes (e.g., biofuel, fermentation), forages produced on lands less suitable for food crop cultivation, and food waste and residuals that are unsuitable for human consumption (FAO, 2025). By converting these low opportunity cost byproduct streams, livestock recycle nutrients back into the food system that otherwise would be lost.

As a result, the food-feed competition for land is reduced (Van Zanten et al., 2018; Wilkinson and Lee, 2018). In addition, circular bioeconomy approaches can recover a host of products from some of the largest organic residue streams in livestock systems and supply chains (Ramirez et al., 2021) including: manures, processing and post-consumer waste streams (e.g., wastewater and municipal sewage). While manures and post-farm gate consumer wastes are becoming increasingly regulated to prevent or limit environmental pollution (e.g., nutrient leaching and runoff, GHG and ammonia emissions), circular bioeconomy approaches aim to shift away from waste management towards safely and efficiently valorizing these streams for the resources they contain (Sommer et al., 2013; Sigurnjak et al., 2020; Sutton et al., 2022) (Fig. 3).

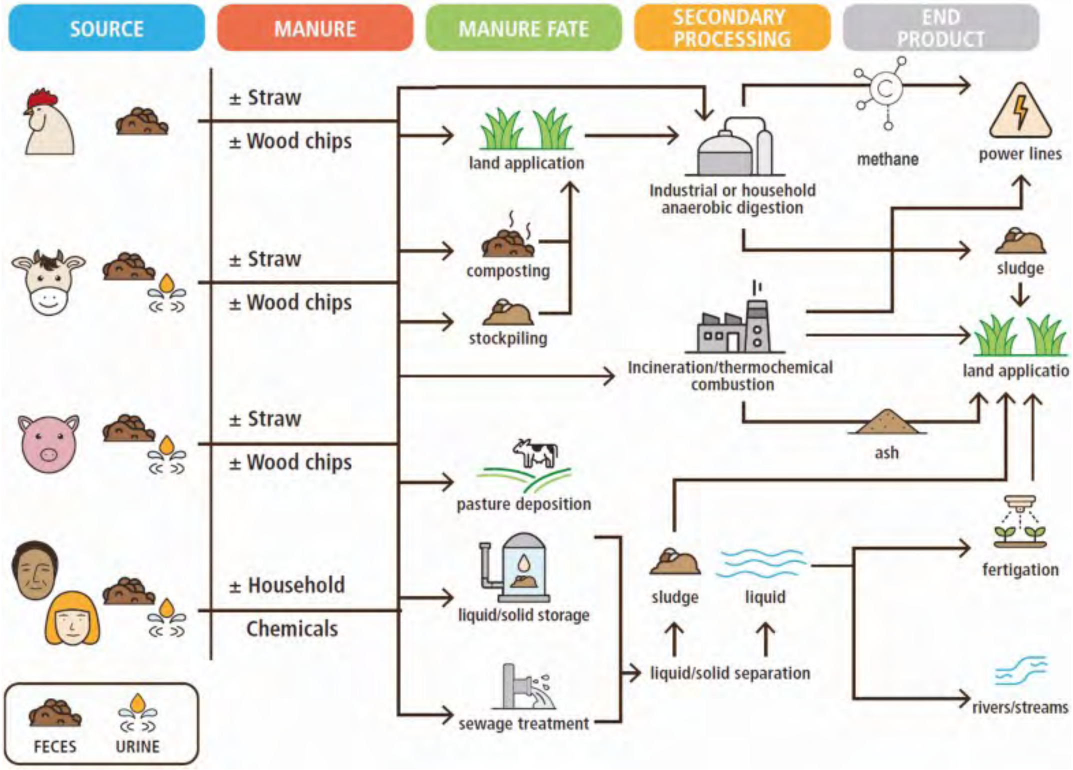

Figure 3: *Schematic illustration of manure and post-consumer waste pathways and opportunities for generating bioenergy and biofertilizer co-products. Source: FAO 2024*

The place of livestock in future farming systems is among the most controversial and complex questions faced today, requiring increased scrutiny and creativity (Van Oort et al., 2024; Whitmee et al., 2024). If net-zero agriculture is to see measurable progress in the future, we will need to consider unprecedented improvisation in establishing new relationships between land and livestock, with greater emphasis on promoting the contribution of livestock to a circular bioeconomy.

A variety of interventions and best management practices are available to simultaneously achieve environmental and economic goals and improve livelihoods. Efforts at a circular bioeconomy and sustainable intensification can promote more efficient resource use, improve soil health, avoid the conversion of natural systems to agriculture, and enhance animal productivity and farmer incomes (McDermott et al., 2010). Nutrient recycling between crop and livestock production (e.g., crop residues for animal feed; manure for soil fertilization) can reduce additional input requirements and feed costs. For example, manure is a key input for enhancing soil nutrients—particularly in sub-Saharan Africa where access to synthetic fertilizers remains low (Herrero et al., 2009)—and provides clear benefits for boosting yields and for improving the incomes of smallholders (Steinfeld et al., 2019). Anaerobic digesters can be used to produce biogas from manure to help meet on-farm energy needs, thereby reducing both GHG emissions and costs (Gerber et al., 2013). There are also more direct policy drivers such as payments for ecosystem services to increase carbon sequestration in rangelands, enhance ecosystem services and aid in the diversification of pastoralist incomes (Herrero et al., 2009).

Indigenous Chicken Farming

Addressing food security on a global scale requires innovative and sustainable approaches capable of meeting growing population demands while providing a sufficient and nutritious food supply (Abbasi et al., 2024). The circular bioeconomy is a sustainable economic model that focuses on reducing waste, reusing resources and recycling materials to create a closed-loop system that minimizes environmental impact. As such, the concept is quite relevant to indigenous chicken farming as it aligns well with the principles of responsible resource management, waste reduction and sustainable agriculture practices (Abbasi et al., 2023).

Indigenous chickens are distinct from commercial or hybrid chicken breeds and are quite well-suited to local environmental conditions and traditional farming practices. They are domesticated chicken breeds with a unique gene pool that have adapted and evolved to specific regions over many generations. As a result, indigenous chickens have gained much attention due to their potential to meet the “triple-bottom-line” standards of nutritional values, environmental friendliness and income generation for rural and urban poor (Abbasi et al., 2023). The triple-bottom-line (TBL) is a sustainability-related construct proposed by Elkington in 1994 to measure the performance of businesses in economic, social and environmental parameters (Abbasi et al., 2024). Thus, TBL serves as a practical framework for sustainability (Abbasi et al., 2023).

In addition, various scholars have reported the socio-economic importance and benefits of smallholder poultry production to several communities, including improved food security and gender equity (Guèye, 2000; Guèye, 2002; Alders and Pym, 2009; Mottet and Tempio; 2017; Wong et al., 2017). For instance, every household in the rural North Rift region of Kenya keeps 5-20 chickens (Okitoi et al., 2007). There is further evidence indicating that when women manage assets and family income, there is improvement in nutrition and education of their children (Khaitsa et al., 2022). Animal agriculture in developing countries, particularly in Africa, is important and can play a significant role in improving people’s livelihoods, particularly for women (Dumas et al., 2016; Van et al., 2020, Ahmed et al., 2021). In East Africa, poultry production is popular in many villages and communities because of its potential as a significant source of income and quality protein (Khaitsa et al., 2022).

The existing literature on indigenous chickens highlights various managerial and operational challenges associated with the lack of an integrated value chain. There are numerous constraints associated with local smallholder farmer poultry systems that include shortage of Extension staff, low productivity of village chickens, a lack of knowledge on best management practices, lack of access to financial services and a proper marketing strategy (Njuki et al., 2011; Wong et al., 2017). Challenges also include fragmented production and a lack of coordination, with numerous small-scale farmers operating independently (Abbasi et al., 2024). Consequently, this fragmentation hinders the coordination of production activities, standardization of practices and consistent quality assurance throughout the value chain. In addition, the absence of an integrated value chain limits access to distribution networks for indigenous chicken products (Abbasi et al., 2024).

In terms of future directions aimed at indigenous chickens, several possibilities present themselves. Abbasi et al. (2024) lists several possible future research avenues related to indigenous chickens that include: 1) comparative studies across diverse regions to gauge the adaptability and effectiveness of integrated farming systems using indigenous chickens within the TBL framework can address regional limitations; 2) enhancing research methods by incorporating both qualitative and quantitative data sources and complementary modelling techniques can provide a more comprehensive perspective; 3) exploring the influence of socioeconomic and cultural factors on system adoption and outcome is critical; 4) assessing long-term sustainability and resilience and examining policy implications are essential; and 5) strategizing ways to scale and disseminate integrated farming systems, including training programs and knowledge sharing, holds significant importance.

These research directions collectively advance sustainable agriculture, benefiting food security, environmental stewardship and economic resilience. However, adoption of any novel innovations at scale is unlikely without significant public support to provide appropriate incentives; the market is unlikely to enable widespread uptake because of technical and economic barriers to adoption (Baltenweck et al., 2020). Although, Baltenweck et al. (2020) indicated that, in addition to providing cheap animal protein, livestock provide other functions such as serving as an asset, acting as a store of wealth for resilience and playing a role as a contributing factor to mixed farming. Indigenous chickens in Africa are, therefore, critical in addressing food security challenges, particularly in the face of climate change and rapid human population growth (Pius et al., 2021). The challenge is to find appropriate ways to incentivize promising circular bioeconomy measures to enhance production efficiency and reduce the environmental costs.

Precision Agriculture/Precision Livestock Farming

Precision agriculture should be viewed as a key tool to help reach a circular bioeconomy. Precision agriculture uses advanced technologies (sensors, data analysis, automation, etc.) to optimize resource use, reduce waste and improve efficiency on farms, which directly supports the main principle of a circular economy—minimizing waste by keeping biological resources in use. Precision agriculture and precision livestock farming does this in several ways, including: 1) resource use optimization (the right amount at the right time in the right location), 2) waste reduction and recycling (lessening the need for new materials and efficiently managing byproducts), 3) closed-loop systems (optimizing feed efficiency and managing manure to reduce GHG emissions and nutrient loss), 4) enhanced sustainability (less reliance on synthetic inputs and reduced impacts on ecosystems) and 5) economic resilience (improved efficiency and novel revenue streams from recycling byproducts that would, otherwise, become wastes in a linear system).

Increased attention must be focused on the technology applicable to the strategy of evolving a circular bioeconomy with an emphasis on the sustainable use of resources (Kumar et al., 2022). This is where PA plays a vital role. Bahmutsky et al. (2024) reported that, according to the International Society of Precision Agriculture: “Precision agriculture is a management strategy based on gathering, processing and analyzing temporal, spatial, and individual plant and animal data and combining it with other information to support farmer management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production.” It is used in both crop and livestock production. Precision livestock farming uses technologies like sensors, software and automated systems to monitor and manage individual animals for improved health, welfare and productivity (Monteiro et al., 2021).

Attention must also focus on the efficient utilization and conservation of water, including recycling, as well as the effective use of manure and its byproducts. A farming system that combines livestock along with the production of crops, by using perennial pastureland, leads to increased profitability, besides building the soil's circular bioeconomy (Zucchella and Previtali, 2019). It assures the welfare of farming societies and invests in the absence of synthetic fertilizers; it improves the productivity of smallholder farmers and encourages the circular bioeconomy by way of reestablishing a symbiotic equilibrium among plants and animals (Boon and Anuga, 2020). Precision farming uses the capability of an information technology system toward maximizing the use of agricultural inputs (e.g., fertilizers, agrochemicals) by supplying "the right quantity, at the right time, in the right position" to ensure that the limited resources required are used effectively at different stages of production to achieve an optimal productivity with minimal environmental effect (Kumar et al., 2022).

Modern crop and livestock production is at a transition point where tradition is meeting technology. We have reached a point where generations of crop and livestock production practices can, going forward, be enhanced by data, automation and insight that serves as the engine to drive the next big step in productivity and sustainability. In the case of PLF, around the globe, from vast agricultural enterprises to small family-run farms, producers are using these technologies to make faster, smarter decisions that improve animal welfare, production efficiency and business resilience. At its core, PLF enhances what producers have always been best at: watching, caring for, interpreting and responding to the needs of their livestock—now with advanced tools and technologies that bring new levels of precision and predictability to a circular bioeconomy.

Unfortunately, when it comes to access, availability and use of advanced artificial intelligence (AI)-type tools and technologies, the world is not a level playing field. For example, the adoption of AI-powered precision agriculture (AI-PA) in Africa faces multifaceted challenges spanning infrastructure, finance, policy, research, technology, socio-economic and educational dimensions. Limited infrastructure, particularly unreliable internet conductivity and power supply, significantly hampers AI adoption, especially in remote and rural areas. The absence of a stable power grid restricts the use of electronic AI devices necessary for many precision agriculture systems, highlighting the need for investments in renewable energy solutions, such as solar power and off-grid technologies. Expanding broadband and mobile network coverage is equally critical to provide farmers with access to real-time data and AI platforms.

High initial investment costs of precision agriculture and AI technologies (cameras, sensors, software, etc.) also present a significant barrier, particularly for smallholder farmers, necessitating improved access to finance and investment opportunities. Inadequate policy frameworks further hinder adoption, with the lack of clear regulations restricting innovation and equitable benefit distribution. Policy incentives are needed to promote research and development collaborations, support data privacy, ensure ethical AI use and establish standards for intellectual property and data sharing. Research and development gaps exacerbate these issues, including insufficient funding, low collaboration intensity, limited decision-support systems and minimal research on crop quality assessment, livestock management practices, environmental auditing and product tracking, with most studies concentrated in relatively developed African countries like South Africa, Nigeria and Kenya (EjimEze, 2025). Many AI-PA technologies remain in the experimental stage and have not been widely implemented, particularly among smallholder farmers, due to complex adoption processes influenced by farm size, farmer experience and socio-economic factors.

The digital divide further exacerbates inequalities, as larger commercial farms gain more benefits than smallholders, with gender disparities and reliance on traditional knowledge affecting adoption rates. Technological challenges, such as insufficient IoT devices, data analytics tools and inconsistent agricultural data on soil, weather, yields and markets, limit AI-driven decision-making. Establishing robust data collection systems, including IoT sensors, satellite monitoring and mobile applications, is crucial to providing real-time insights. Additionally, significant educational and training gaps among farmers and agricultural professionals hinder AI utilization, highlighting the need for additional trained Extension personnel and capacity-building programs that enhance AI literacy and practical application skills. Overall, the barriers to AI-PA adoption in Africa are deeply intertwined, arising from socio-economic, technological and policy-related factors, with the digital divide reflecting the unequal access to AI technologies and advanced AI-powered precision agricultural practices across Africa (EjimEze, 2025).

Summary

Finding strategies that will provide safe and nutritious food to nearly 10 billion people by 2050 while also protecting the long-term health of the planet is one of the greatest challenges we face. Implementing a circular bioeconomy can offer solutions to address global challenges such as resource depletion, biodiversity loss, waste management and environmental impacts. There are challenges, nonetheless, with switching from a linear food production model to a circular bioeconomy. A top priority must be to address food waste. When food is wasted, all the resources used in its production, including water, land, energy and labor, are also wasted. The integration of food waste into the circular bioeconomy offers multiple environmental, economic and social benefits, environmentally, economically and socially. In addition, the importance of livestock to a circular bioeconomy must be better recognized and utilized.

The livestock sector, particularly in middle- and low-income regions, is still decades behind in terms of technology, policy and business model innovation. It lags far behind other sectors in attracting investment and finance. We should recognize that, in some cases, moving forward in the livestock sector may entail returning to the past and reviving restorative practices that may include returning marginal lands to natural vegetation, developing multifunctional landscapes, perennializing farming, reestablishing animal-crop symbioses, resolving the nitrogen paradox, adopting holistic perspectives and rethinking economic rewards.

Much can be learned from traditional practices such as indigenous chicken farming, as it aligns well with the principles of responsible resource management, waste reduction and sustainable agriculture practices. These are the same principles that drive precision agriculture and precision livestock farming. As we transition from a linear production system to a circular bioeconomy, especially where livestock are concerned, precision agriculture and PLF technologies offer a pathway to proactive health management, increased productivity, improved animal welfare and resource optimization in reaching a circular bioeconomy for the common good of humankind, the environment and the economy. Still, for AI-driven precision agriculture to reach its full potential, we must level the global playing field and make technologies available to everyone, particularly smallholder farmers across Africa who may benefit most from the technologies.

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