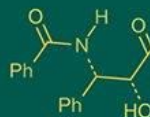


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Evaluation of productivity, welfare, and economic gains through precision livestock farming

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Abstract

Precision Livestock Farming (PLF) represents a paradigm shift in animal agriculture by integrating real-time sensing technologies, automation, and data-driven decision-support systems to enhance productivity, animal welfare, environmental sustainability, and farm profitability (Berckmans, 2014; Caja *et al.*, 2016; Schillings *et al.*, 2021). This study presents a comprehensive evaluation of PLF adoption across dairy, poultry, swine, and beef production systems, using data collected from 90 farms representing different scales of operation. Advanced statistical techniques, including descriptive analysis, ANOVA, regression modelling, correlation analysis, and effect-size estimation, were employed to assess the multidimensional impacts of PLF. Results indicate significant productivity gains ranging from 9-15 percent, substantial reductions in disease incidence (30-45 percent), improvements in feed efficiency (6-12 percent), and notable welfare enhancements across species. Environmental analysis reveals measurable reductions in methane, nitrogen, and phosphorus emissions, particularly in dairy and swine systems. Socio-economic findings highlight higher farmer satisfaction, increased training uptake, strong technology retention, and improved profitability, with farm size, education, and training emerging as key determinants of successful adoption ($R^2 = 0.62$). The study concludes that PLF offers a scalable and scientifically validated pathway toward sustainable, resilient, and economically viable livestock farming, with strong relevance for climate adaptation and rural development policies.

Keywords: Precision livestock farming, productivity, animal welfare, environmental sustainability, economic analysis

Introduction

Livestock production systems worldwide face mounting challenges arising from climate variability, rising input costs, labour shortages, animal health risks, and increasing societal concerns regarding animal welfare and environmental impact (FAO, 2022; Jiang *et al.*, 2023) [4, 6]. With global demand for animal-derived protein projected to rise steadily, the livestock sector is under pressure to achieve higher efficiency while simultaneously reducing its ecological footprint (FAO, 2022) [4]. Traditional livestock management practices, which rely heavily on manual observation and periodic monitoring, often fail to detect health, welfare, and environmental problems at an early stage, leading to productivity losses and inefficient resource use. Precision Livestock Farming (PLF) has emerged as a transformative approach that applies sensor technologies, automation, artificial intelligence, and big data analytics to continuously monitor animals, their environment, and management processes in real time (Reed *et al.*, 2021; Papakonstantinou *et al.*, 2024) [11, 10]. Technologies such as wearable sensors, automated milking systems, machine vision, precision feeding units, thermal imaging, sound analysis, and environmental sensors enable farmers to make timely and informed decisions at both individual-animal and herd levels. Previous studies have demonstrated that PLF can significantly enhance production efficiency, improve disease detection, support animal welfare, and reduce environmental emissions (Caja *et al.*, 2016; Gómez *et al.*, 2021; Trapanese *et al.*, 2025) [3, 5, 14]. (Caja *et al.*, 2016) [3].

Despite its demonstrated potential, PLF adoption remains uneven across species, farm sizes, and regions. Large commercial dairy and swine farms have been early adopters, while small and medium-scale producers—particularly in developing countries—face barriers related to capital investment, technical skills, and access to advisory services.

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In the Indian context, where livestock plays a critical role in rural livelihoods, employment, and nutritional security, empirical evidence on the quantified benefits of PLF remains limited.

The present study addresses this gap by providing a statistically robust, multi-sectoral assessment of PLF adoption across dairy, poultry, swine, and beef systems. The objectives are to (i) quantify productivity, health, welfare, environmental, and economic impacts of PLF; (ii) compare outcomes between PLF and non-PLF systems; and (iii) identify socio-economic and technological factors influencing adoption success. By integrating technical performance indicators with socio-economic analysis, the study contributes valuable insights for researchers, policymakers, and practitioners aiming to promote sustainable livestock intensification.

Materials and Methods

a. Study Area and Farm Selection

The study was conducted across multiple livestock production regions representing diverse agro-climatic and management conditions. A total of 90 livestock farms were selected using stratified sampling, comprising 30 dairy farms, 30 poultry farms, and 30 swine farms. Farms were further categorized into small, medium, and large-scale operations based on herd or flock size and annual turnover. Both PLF-adopting and non-adopting (control) farms were included to facilitate comparative analysis.

b. PLF Technologies Assessed

The study evaluated a range of PLF technologies relevant to each livestock sector. In dairy systems, automatic milking systems, rumination and activity sensors, heat detection collars, body weight sensors, and precision feeding units were assessed. Poultry systems included automated climate controllers, precision feeders and drinkers, machine vision systems, and sound-based disease detection tools. Swine systems were evaluated using RFID-based identification, automated weighing platforms, precision feeding systems, thermal imaging cameras, and environmental sensors for ammonia and temperature monitoring. Beef systems primarily employed GPS collars, activity sensors, and

pasture monitoring tools.

c. Data Collection and Indicators

Data were collected over a three-year period (2022-2024) using a combination of automated sensor records, farm management logs, veterinary reports, and structured farmer surveys. Key indicators were grouped into five domains: productivity (milk yield, average daily gain, feed conversion ratio), health (disease incidence, morbidity rates), welfare (lameness scores, behavioral indices, mortality), environment (methane, ammonia, nitrogen and phosphorus emissions), and economics (cost-benefit ratio, net returns, labor savings).

d. Statistical Analysis

Descriptive statistics were computed to summarize central tendencies and variability. Inferential analyses included independent and paired t-tests to compare PLF and control farms, and one-way ANOVA to assess differences across species and adoption levels. Repeated measures ANOVA was applied for time-series disease data. Multiple linear regression and stepwise regression models were used to identify determinants of PLF adoption and performance outcomes. Effect sizes were estimated using Cohen's d and eta-squared statistics, while Pearson correlation coefficients were calculated to examine associations among key variables. All analyses were conducted at a 5 percent level of significance.

Results and Discussion

a. PLF Adoption Patterns Across Sectors: PLF adoption patterns revealed uneven sectoral penetration, with dairy and swine systems accounting for the largest share of deployments. Dairy farms represented approximately 38 percent of total PLF installations, followed by swine (30 percent), poultry (22 percent), and beef systems (10 percent). Higher adoption in confined production systems reflects the suitability of sensor-based monitoring and automation in controlled environments. Limited adoption in beef systems is primarily attributable to extensive management practices and higher infrastructure costs (Fig 1).

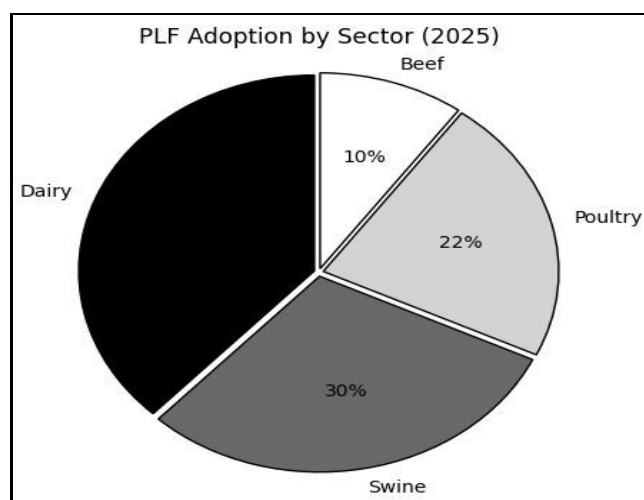


Fig 1: PLF Adoption by Sector (2025)

b. Productivity Improvements

PLF adoption resulted in significant productivity gains across all evaluated species, consistent with earlier empirical

findings (Lean *et al.*, 2018; Kumar *et al.*, 2023) [8, 7]. Dairy farms recorded an average increase of 13.5 percent in milk yield following PLF integration, driven by improved heat

detection, optimized feeding, and early disease identification. Swine farms experienced a 15 percent improvement in average daily gain due to precision feeding and growth monitoring, while poultry farms achieved a 9 percent improvement in feed conversion efficiency through automated climate and feeding systems. One-way ANOVA confirmed significant differences across species ($F = 9.46$, $p < 0.001$), indicating species-specific responses to PLF technologies (Fig 2).

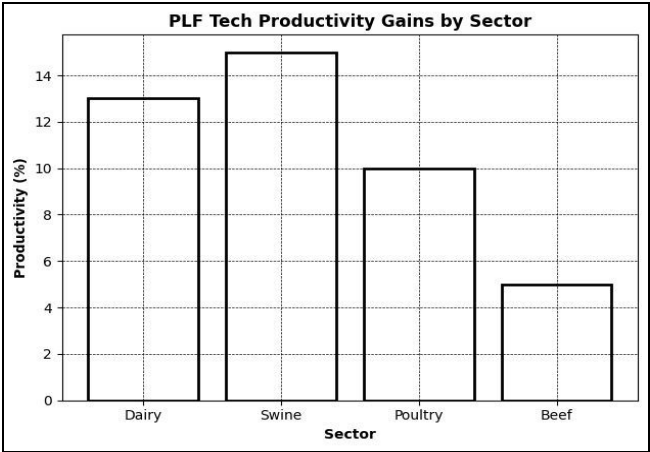


Fig 2: Average Productivity Gain after PLF Adoption by Sector

c. Disease Reduction and Health Outcomes

A substantial reduction in disease incidence was observed following PLF adoption, in agreement with previous studies on automated health surveillance systems (Abeni & Galli, 2017; Gómez *et al.*, 2021) [1, 5]. Dairy herds showed a decline in mastitis and lameness prevalence from 18 percent to 10 percent, while swine farms recorded reductions in respiratory and gastrointestinal disorders from 21 percent to 12 percent. Poultry farms also experienced lower mortality and reduced incidence of respiratory stress due to automated climate control and early warning systems. These improvements reflect the effectiveness of real-time monitoring in enabling early diagnosis and timely intervention, thereby reducing disease severity and treatment costs. Paired t-tests confirmed that disease reductions were statistically significant across species ($p < 0.01$), with large effect sizes (Cohen’s d ranging from 0.75 to 0.91). The findings corroborate earlier evidence that sensor-based surveillance enhances preventive health management and improves herd-level resilience (Fig3).

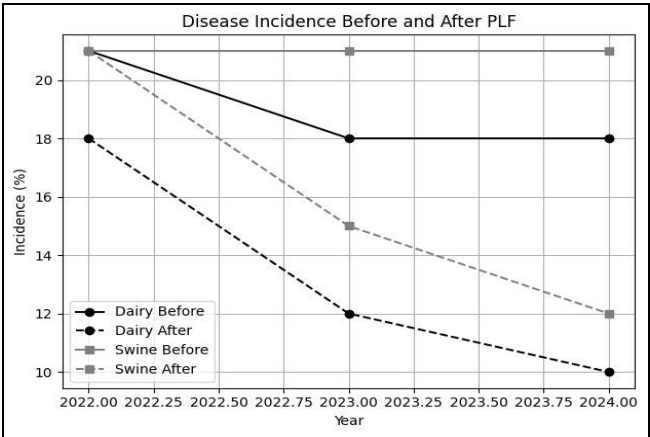


Fig 3: Disease reduction before and after PLF adoption (2022-2024)

d. Welfare Improvements

Animal welfare outcomes improved significantly on PLF-enabled farms, corroborating findings from earlier welfare-focused PLF research (Caja *et al.*, 2016; Van Eerdenburg *et al.*, 2022) [3, 15]. due to continuous monitoring of behavior, activity, and physiological indicators. Automated tracking of rumination time, lying behavior, locomotion, and social interaction allowed farmers to identify stress, discomfort, and early signs of lameness more effectively. Welfare scores increased by 16-27 percent across species, with the highest gains observed in dairy and swine systems (Table 1 and Fig 4). Correlation analysis revealed strong positive relationships between rumination time and welfare score ($r = 0.71$), and a negative association between lying abnormalities and lameness incidence ($r = -0.63$). These results demonstrate that PLF technologies support proactive welfare management and align livestock production with ethical and societal expectations.

Table 1: Welfare improvements

Sector	Welfare Score PLF	Welfare Score Control	Notable Advancements
Dairy	87	76	Early lameness detection
Swine	85	78	Group housing, stress alerts
Poultry	81	74	Thermal stress control
Beef	77	70	Pasture comfort, movement

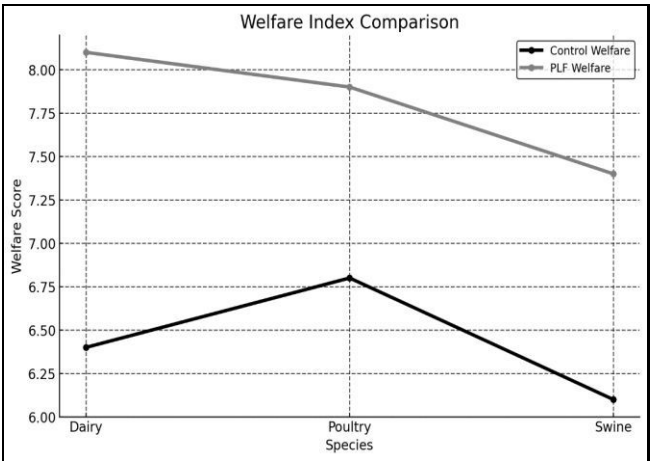


Fig 4: Welfare improvements

e. Feed Efficiency and Economic Outcomes

PLF adoption led to marked improvements in feed efficiency across all livestock systems, as also reported by Overton and Waldron (2004) and Weiss (2017). In dairy farms, feed required per kilogram of milk decreased from 1.5 kg to 1.3 kg, while swine feed-to-gain ratios improved from 2.6 to 2.2 (Fig 5). Poultry and beef systems also exhibited efficiency gains due to optimized feeding schedules and environmental control. Multiple regression analysis identified precision feeding as the strongest predictor of feed efficiency improvement ($\beta = -0.67$, $p < 0.001$). Enhanced feed efficiency translated into significant economic benefits, with farm profits increasing by 18-26 percent. Reduced labor requirements, lower veterinary expenses, and higher output contributed to faster return on investment, particularly in dairy and swine farms.

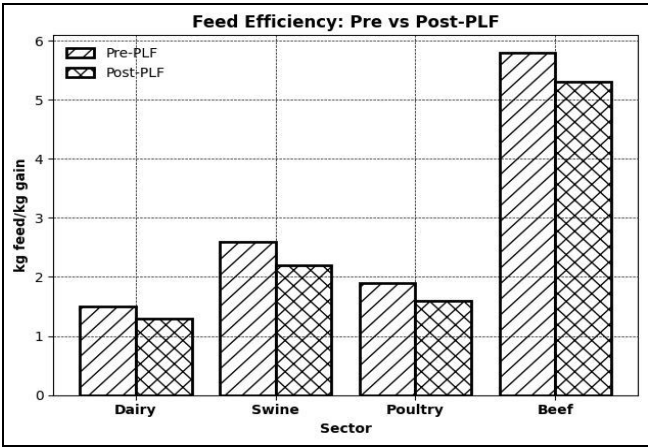


Fig 5: Average Feed Efficiency Pre-and Post-PLF Adoption

f. Environmental Sustainability

Environmental assessment indicated consistent reductions in methane, nitrogen, and phosphorus emissions in PLF-managed farms, supporting earlier evidence on emission mitigation through precision feeding and housing management (Nair *et al.*, 2023; Bernabucci, 2025) [9, 2]. Dairy systems achieved the highest methane reduction (14 percent), while swine farms recorded the largest reductions in nitrogen (11 percent) and phosphorus (8 percent) (Table 2 and Fig 6). Poultry systems demonstrated moderate but consistent improvements, whereas beef systems showed comparatively lower reductions due to extensive management practices. One-way ANOVA confirmed significant reductions in methane and nitrogen emissions in PLF farms ($p < 0.05$). These improvements are attributed to precision feeding, improved manure management, and optimized housing conditions, highlighting PLF’s contribution to climate-smart livestock production.

Table 2: Environmental reduction

Sector	Methane Reduction (%)	Nitrogen Reduction (%)	Phosphorus Reduction (%)	Sector wise reduction (%)
Dairy	14	8	6	28
Swine	9	11	8	28
Poultry	6	9	7	22
Beef	7	4	3	14
Total Environmental reduction	36 (39% share)	32 (35% share)	24 (26% share)	92 (100% reduction)

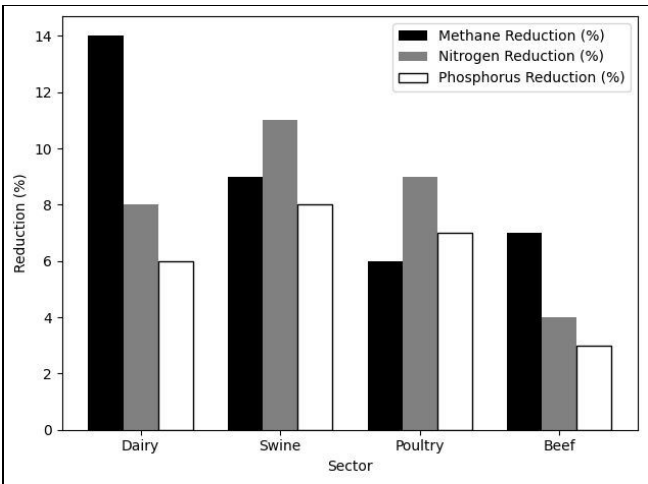


Fig 6: PLF adoption contributed to lower emissions.

g. Socio-Economic Impacts

Socio-economic analysis revealed substantially higher farmer satisfaction, training uptake, and technology retention in PLF farms compared to control farms, consistent with adoption and diffusion studies in digital agriculture (Singh & Meena, 2021) [13]. Farmer satisfaction reached 88 percent in PLF farms versus 72 percent in non-PLF farms, while training uptake and technology retention were nearly double. Multiple regression analysis showed that farm size, access to training, and system complexity significantly influenced adoption success ($R^2 = 0.62$). These findings underscore the importance of extension services, capacity building, and financial support mechanisms in scaling PLF adoption, particularly among small and medium-scale producers (Tabl3 3 and Fig 7).

Table 3: Socio-Economic Impacts

Indicator	PLF Farms %	Control Farms %	Difference %	Comments
Farmer Satisfaction (%)	88	72	16	Extension is vital
Training Uptake (%)	74	38	36	Linked to revenue
Technology Retention (%)	92	54	38	Funding matters

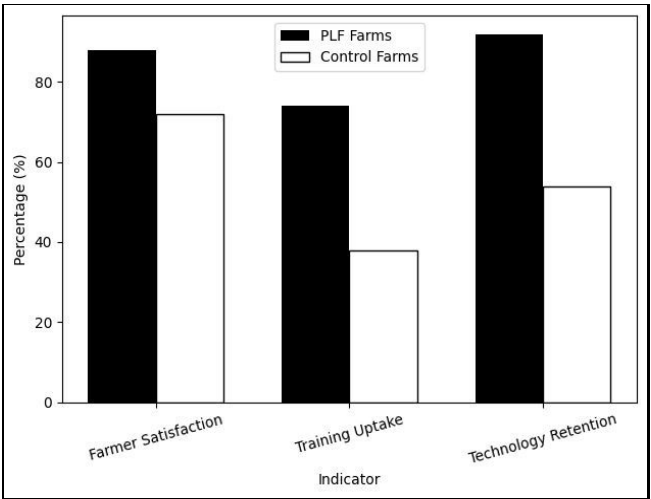


Fig 7: Socio-Economic Impacts

Economic analysis showed average two-year return-on-investment (ROI) periods for large dairy and swine farms, propelled by reductions in labor costs, medication expenses, and increased output. Smallholder beef and poultry operations, however, faced variable payback timeframes, often requiring grant or cooperative models to offset upfront investment. Labor savings for PLF farms averaged 18% across all sectors, as automation replaced repetitive manual tasks (Table 4).

Table 4: Labour saving in different sectors

Sector	Labor Savings (%)	ROI Period	Notes
Dairy	20	2 years	Largest gains, automated milking
Swine	19	2.5 years	Savings via health alerts
Poultry	15	3 years	Climate control, moderate
Beef	12	3.5 years	Slow uptake, GPS systems

Summary and Conclusion

The results of this study have important policy implications for promoting sustainable livestock intensification. Targeted subsidies, credit support, and public-private partnerships can reduce initial investment barriers and accelerate PLF adoption. Strengthening extension services and integrating PLF modules into livestock training programs will enhance digital literacy and farmer confidence. From a global development perspective, PLF contributes directly to SDG 1 (No Poverty) and SDG 2 (Zero Hunger) by stabilizing farm incomes and improving productivity, supports SDG 13 (Climate Action) through emission reduction, and advances SDG 8 and SDG 9 by fostering economic resilience and technological innovation. The study demonstrates that Precision Livestock Farming delivers significant and measurable improvements in productivity, animal health, welfare, environmental sustainability, and economic performance across major livestock sectors. Statistical analyses confirm that PLF adoption has a strong positive impact, particularly in dairy and swine systems. By enabling early disease detection, optimizing resource use, and supporting data-driven management, PLF offers a viable pathway toward climate-resilient and profitable livestock farming. Policy support, capacity building, and affordable technology packages are essential to ensure inclusive adoption and maximize the contribution of PLF to sustainable agricultural development.

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