Policy Paper 57

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Preface

India's livestock production systems have undergone significant transformation over the past five decades, playing a crucial role in enhancing the country's food and nutritional security. The impact of this transformation extends beyond food and nutrition and encompasses broader socio-economic benefits. Livestock are an important source of livelihood for small-scale farmers and landless laborers and function as a buffer against income crises due to crop failures. Livestock generates a consistent income stream; hence, growth in the livestock sector has a relatively larger effect on poverty reduction.

The transformation in livestock production systems has been driven by a complex set of factors, including technological advancements in animal genetics, breeding, health, and nutrition, and improvements in animal breeding and veterinary service delivery systems. However, there is a notable lack of comprehensive economic assessments of such interventions, particularly technological advancements in animal genetics and breeding. This paper fills this research gap by evaluating the economic impact of enhanced germplasm across different animal species. The findings underscore the significant economic advantages derived from the adoption of improved germplasm, thereby providing a compelling argument for the prioritization of animal genetics and breeding research, as well as its dissemination. I hope the findings reported in this study prove valuable to research administrators and policymakers in their decision-making processes.

Pratap Singh Birthal
Director, ICAR-NIAP

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(Authors)

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Executive Summary

Technological advancements in animal genetics and breeding, disease diagnosis and management, and feeding and nutrition have resulted in substantial improvements in animal productivity and the production of animal-sourced foods in India, ensuring food security and nutrition, particularly for the disadvantaged populations. However, the production of sufficient animal-sourced food remains challenging. With increasing disposable income and urbanization, the demand for animal-sourced foods is projected to rise more rapidly than that for staple food grains. Projections indicate that by 2047, India will require 480 million tons of milk, 21 million tons of meat, and 16 million tons of eggs (GoI, 2024b).

India has a large livestock population of cattle, buffaloes, goats, sheep, and poultry. However, the productivity of these animals remains notably low compared with global standards because of several factors, including traditional farming practices, limited access to modern technologies, inadequate veterinary care, and suboptimal nutrition. Historically, growth in the production of animal-source foods has occurred primarily because of an increase in the number of animals. The sustainability of number-driven growth is questionable, particularly considering the persistent feed and fodder shortage. Consequently, the focus must shift towards enhancing productivity rather than simply increasing livestock numbers. This transition necessitates a multifaceted approach, including improving the supply of feed and fodder, expanding animal health infrastructure, and improving genetic potential.

Genetic enhancement strategies have proven to be the cornerstone of improved livestock productivity. This study assesses the economic impact of improved germplasm of various species. By examining the Frieswal breed of cattle, known for its higher milk yield; the Barbari goat breed, recognized for its meat quality; the Avishan sheep breed, valued for its meat yield; the Rani pig breed, noted for its higher carcass weight; and the Vanaraja and Gramapriya varieties of backyard poultry, prized for their dual-purpose capabilities, this study offers a holistic view of genetic improvement outcomes in diverse species.

Economic evaluation of these genetically enhanced breeds/varieties serves multiple purposes: First, it quantifies the economic benefits of the improved germplasm, providing tangible evidence of its impact on farmers' livelihoods and the agricultural economy; second, this assessment offers critical insights into the effectiveness of current breeding programs, highlighting their success and potential areas for improvement, which is valuable for policymakers and research administrators to refine existing strategies and develop new approaches to genetic enhancement.

Key Findings

- **Higher productivity across species**: Improved livestock germplasm consistently demonstrated superior performance compared to traditional or non-descript counterparts. Frieswal crossbred cows recorded earlier age at maturity, age at first calving, shorter rearing period of heifer to breedable age, reduced incidence of delayed conception, lesser number of services required per conception, lesser service period and significantly higer lactation yield, than other crossbred counterparts. Barbari goats exhibited earlier age at first breeding, higher twinning percentage, higher number of kids born per parturition, shorter service period and higher marketable body weight (by 22%). Avishan sheep showed increased twinning percentages, lower service period and better carcass yield (by 9%). Rani pig yielded significantly greater carcass weight due to higher litter size and growth rates. In backyard poultry systems, Vanaraja and Gramapriya birds exhibited lower mortality rate, lower maturity time, higher hatching rate, and outperformed local breeds by 67–167% in egg output respectively.
- **Accelerated performance trajectory through reproductive efficiency:** Improved germplasm possesses inherent reproductive and growth efficiencies — such as shorter calving/kidding intervals, higher conception rates, and faster growth — which, when simulated over multiple reproductive cycles, translate into significantly faster gains in productivity and herd output compared to traditional breeds. These biological advantages compound over time, resulting in higher cumulative output and income in representative production environments.
- **Economic viability and profitability**: All improved germplasm demonstrated positive economic benefits over traditional breeds. Benefit–Cost (BC) ratios ranged from 1.57:1 (Frieswal) to 3.85:1 (Vanaraja), with Barbari (2.13:1), Avishan (1.76:1), and Rani pigs (1.59:1) performing strongly. Net present value analysis reinforced the long-term profitability of genetic investments, even under moderate input costs.
- **Sustainable resource use**: Improved breeds achieved higher output per unit of feed and other inputs, promoting resource efficiency.

- **Significant cumulative national gains**: The sustained adoption of improved germplasm across major livestock species can contribute substantial economic benefits at the national level, enhancing productivity, income, and food security without proportionate resource use expansion.

These findings have important implications for animal science research and development. First, animal genetics and breeding research is capital-intensive and involves a prolonged gestation period, underscoring the critical importance of sustained investment in this area. The returns on investment in animal science research are significantly larger than those in crop science research (Kandpal et al., 2024). Second, high-yielding breeds are not high-yielding in themselves; to manifest their potential, these breeds require high-quality feed, better healthcare, and improved management practices. Consequently, the importance of concurrent investments in animal breeding and health infrastructure, as well as in the manufacture of quality feed, should not be underestimated. Expanding access to subsidies, credit, and insurance is essential to offset initial adoption costs and de-risk smallholders investing in improved germplasm and complementary technologies, underscoring the need for a comprehensive approach to livestock development.

Third, the gains from research investment remain limited in the absence of institutional mechanisms for the multiplication of improved germplasm and its distribution to farming communities. The extension system, which serves as a bridge between research and farming communities, remains underdeveloped, even though investment in extension generates substantial returns (Kandpal et al., 2024). There is a need to establish dedicated extension modules focusing on the adoption and management of specific improved germplasm, incorporating breed-specific best practices in feeding, breeding, and disease prevention. Priority should be given to building grassroots breeder networks and local value chains, particularly for backyard poultry varieties in smallholder-dominated regions. Further, species-specific infrastructure—such as decentralized semen stations for Frieswal cattle, buck distribution centers for improved meat germplasm, and government-certified hatcheries for improved backyard poultry varieties—needs to be strengthened.

1 Introduction

India's food system has undergone a significant transformation over the past four decades. Driven by increasing per capita income, growing urbanization, and changing lifestyles, dietary patterns have experienced a notable transition from staple cereals to nutritious high-value commodities, including fruits, vegetables, milk, meat, eggs, and fish. The share of dairy products in household consumption expenditure on food increased from 7.5% in 2011-12 to 8.5%, in 2022-23 while that of eggs, fish, and meat increased from 4.4% in 2011-12 to 5.2% in 2022-23 (Kapoor et al., 2024). This dietary transition is anticipated to continue if the past trends in per capita income and urbanization persist.

By 2047, India is projected to achieve developed nation status, supported by an anticipated annual economic growth rate of approximately 8%.The population is projected to reach 1.6 billion, half of which will reside in urban areas (GoI, 2024b). The consumption of animal-source foods demonstrates a greater responsiveness to income changes; consequently, with accelerated economic growth, the demand for animal-source foods by 2047 is projected to be more than twice the current demand. The demand for milk, meat, and eggs is expected to increase to 480 million tons, 21 million tons, and 16 million tons, respectively (GoI, 2024b).

Historically, the increasing demand for animal-source food products in India has been met through domestic production. From 1980-81 to 2023-24, milk production increased from 31.6 million tons to 239.3 million tons, meat production from 1.9 million tons to 10.25 million tons, and egg production from 10.06 thousand million to 142.77 thousand million (GoI, 2024a). This increase in livestock production is primarily due to the increase in the number of animals.

The productivity of almost all animal species in India is substantially lower than the global averages. For instance, the average milk yield of a cow in India is approximately 1800 kg/annum, which is 34%

lower than the global average (GoI, 2021). Similarly, the meat yields of most species are significantly lower. Multiple factors contribute to low livestock productivity. India possesses a substantial population of diverse livestock species, including 193.46 million cattle, 109.85 million buffaloes, 223.14 million small ruminants, 9.06 million pigs, and 851.81 million poultry birds (GoI, 2019a.). However, the capacity of agricultural land to support this large population is limited, and the scarcity of feed and fodder has been a significant constraint on improving animal productivity (Birthal and Jha, 2005). Inadequate provision of animal health and breeding services is another crucial factor contributing to low animal productivity. Despite considerable advancements in animal breeding infrastructure, the success rate of Artificial Inseminations (AIs) seldom exceeds 40% (NAAS, 2020).

Livestock play diverse roles in addition to food production. They are instrumental in enhancing agricultural resilience, alleviating poverty, addressing malnutrition, promoting women's empowerment, and narrowing developmental disparities (Birthal and Negi, 2012; Jumrani and Birthal, 2015). In 2022-23, the livestock sector accounted for 30.38% of the agricultural gross domestic product (AgGDP). The period from 2014–15 to 2022–23 witnessed an exceptional annual growth rate of approximately 7.38% in the Gross Value Added (GVA) from the livestock sector (GoI, 2024a).

Two notable characteristics of India's livestock production system warrant further attention. First, animal resources are concentrated at the lower end of land distribution (Jumrani and Birthal, 2015). More than 70% of the population of almost all species is controlled by marginal and small farmers (GoI, 2019b), who represent the economically disadvantaged section of rural India. Second, compared with food grains, the consumption of animal-source foods is more responsive to income changes; consequently, their demand is projected to increase more rapidly as the impoverished population experiences economic improvement. Given these factors, at a comparable growth rate, livestock have a more significant pro-poor effect than crops.

Although the expansion of livestock production is considered advantageous in several aspects, number-driven growth is subject to various biotic and abiotic pressures, including climate change, and consequently, future growth must result from improvements in animal productivity, which can be achieved through genetic enhancement. The

National Agricultural Research System (including the Indian Council of Agricultural Research and State Agricultural/Veterinary Universities) has made substantial efforts to enhance the genetic potential of diverse livestock species. However, despite these initiatives, a significant gap remains in our understanding of the economic impact of genetic enhancement, and the lack of empirical evidence makes it challenging to assess the true value and effectiveness of these interventions, highlighting the need for a comprehensive study to guide future research and policy decisions regarding genetic improvement.

Several studies on the performance evaluation of improved germplasm and their impact on economic parameters are available in the Indian context (Jain et al., 2025). However, it is noteworthy that the economic impact assessment of improved livestock germplasm in India has mainly focused on ex-post approaches. Singh and Gurnani (2004) conducted a study on the performance evaluation of crossbred cattle genotypes, such as Karan Fries and Karan Swiss, developed by ICAR-NDRI. The study was conducted from 1982 to 1992, and the authors evaluated parameters such as milk yield, lactation performance, and calving interval. This study was based on long-term field-level observations of the realized productivity and profitability outcomes under varied husbandry conditions.

Among other ex-post studies, Hegde (2018) assessed the impact of crossbreeding and upgrading of non-descript cattle and buffaloes in eight major states of India and reported a 200% to 400% increase in the income of dairy farmers. Patil and Udo (1997) quantified the impact of crossbreeding at the farm level in mixed farm systems in Gujarat and reported that crossbred animals increased livestock gross margins by 64% and household income by 22%. Widi et al. (2020) evaluated the impact of crossbreeding with exotic beef breeds in smallholder mixed farms in Central Java, Indonesia, and reported that crossbreeding contributes to increased meat production at the national level; however, it does not necessarily guarantee improvements in economic benefits at the farm level or environmental performance. Prasad et al. (2013) carried out an impact assessment study on impact of Barbari goat in Uttar Pradesh and reported that net return per goat/annum was 31.80% higher over local breeds. Singh et al. (2019) assessed the economic impact of Vanaraja backyard poultry variety in Sikkim and reported significantly higher net income for Vanaraja as compared to that of local breeds.

The above review of existing impact assessments reveals that most studies are based on primary data and focus on performance differentials between improved and indigenous germplasm. Although these assessments provide valuable retrospective evidence, they fail to account for the biological and economic dynamics underlying trait transmission and herd evolution over time.

The specific objectives of the study are: (i) to assess the economic impacts of improved germplasm in comparison to traditional or nondescript breeds, (ii) to provide a realistic assessment of the potential benefits and challenges associated with genetic enhancement in livestock and poultry, which is useful for farmers, policymakers, and input and processing industries to make informed decisions regarding the allocation of resources for a more sustainable and efficient livestock production system.

To achieve these objectives, the present study applies a dynamic, system-based modelling approach that integrates species-specific biological parameters – including reproduction, growth, and productivity traits. The potential benefits and challenges were assessed, taking into account evolving herd structures and production levels.

2 Data and Methods

2.1 Data

The data utilized in this study for both improved and traditional germplasms were primarily sourced from primary field-level data collection, specifically Focus Group Discussions (FGDs) with adopters and non-adopters, supplemented by institutional records. This approach ensured that the performance and cost parameters for all genotypes were derived from comparable field conditions and not from aggregated national statistics, such as the Basic Animal Husbandry Statistics (BAHS), which were used only for contextual national-level population and production data.

FGDs were conducted, comprising both adopters and non-adopters of the improved germplasm, to gather information on the production and reproduction parameters for the economic life cycle of the species to supplement the information obtained from the data resources of the scientific institutes. Average production and reproduction parameters for improved and traditional germplasms were derived using data collected through FGDs with both beneficiary (who have adopted the improved germplasm) and non-beneficiary farmers (who own traditional breeds). Each FGD was facilitated by Institute Experts (scientists involved in the development/ dissemination of the improved germplasm). Various parameters, including productivity, breeding cycles, and diseases, are discussed. Data from the FGDs were cross-validated with available records at the institutes and through expert reviews.

FGDs were conducted in a mix of rural settings in different states. For Frieswal Cattle, the FGDs were conducted in the Sitarganj and Khamara blocks of Udham Singh Nagar district in the northern state of Uttarakhand, where the farming practices are representative of typical North Indian plains agro-systems. For Barbari goats, FGDs were held in the Mathura district of Uttar Pradesh and Bharatpur district of Rajasthan, the traditional breeding tract of the Barbari breed. These regions are characterized by mixed agricultural systems, which enable the evaluation of the adaptability and economic impact of improved germplasms. In the case of Avishan Sheep, the assessments took place in the Tonk district of

Rajasthan, which typifies the semi-arid regions of central India, providing insights into livestock farming under arid to semi-arid conditions. For Rani pigs, data were gathered from the northeastern region of India, specifically from Assam. This region features a subtropical climate, offering perspectives on livestock management in environments with high humidity and rainfall. In the case of Vanaraja and Gramapriya poultry varieties, FGDs were held in the Adilabad district of Telangana, representing conditions in southern India, from semi-arid zones to areas with intensive agricultural practices.

Comparisons between improved and traditional germplasms are exclusively made within the same environmental and management contexts, that is, at the field level, thus avoiding the skewed assessment of the germplasms' performance under organized farming conditions.

All production and reproduction parameters and cost and return components used in the simulation and cost–benefit analysis were derived from FGDs conducted with livestock-keeping households managing the improved and traditional germplasms. The biological assumptions, including calving intervals, age at maturity, and yield levels, are summarized in species- and breed-specific tables in the results section. Similarly, cost parameters, including feed, fodder, and veterinary expenses, are reported separately for improved and traditional germplasm. These tables provide the underlying assumptions and represent field-level averages reported by farmers rather than hypothetical or literature-derived values. This bottom-up, stakeholder-informed parameterization forms the foundation of the System Dynamic Model (SDM) projections and economic feasibility analysis. Data on livestock population and production were compiled from the Basic Animal Husbandry Statistics (2024) and Livestock Census (2019).

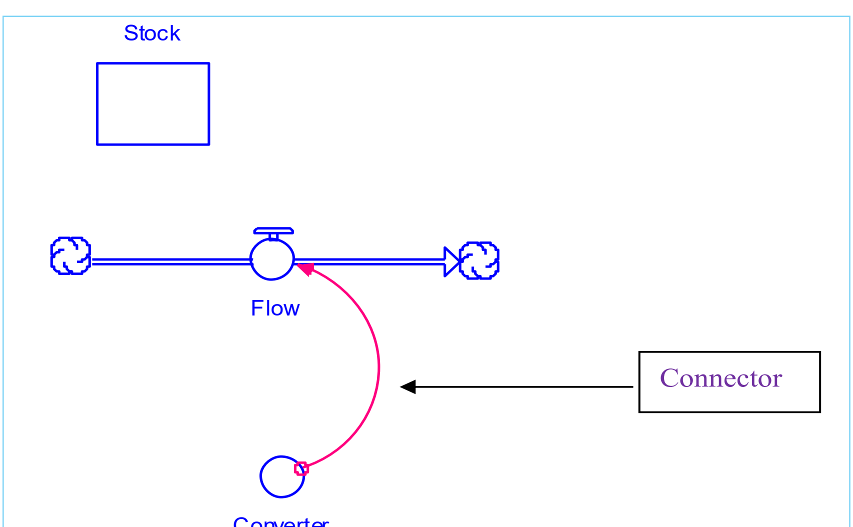
It is important to note the scope of this assessment in this regard. While national data, such as the NSS 77th Round (2019), indicate that a significant majority of India's livestock are owned by small and marginal farmers, this study focuses on evaluating the economic feasibility and productivity potential of the improved germplasm. Our model does not explicitly simulate subsequent changes in livestock ownership patterns or distribution across different farm sizes that may result from adopting these technologies. This focus on the inherent economic potential of germplasm allows for a clear assessment of its benefits, while acknowledging that patterns of adoption and equity are critical areas for separate, targeted research.

2.2 System dynamic modeling approach

The SDM employed in this study serves as a powerful ex-ante tool for impact assessment. It captures the linkages between the production and reproduction parameters of a livestock species and the potential impact of any intervention on reproductive efficiency to optimize the breedable population size. This model can also convert the typical qualitative aspects of production into quantifiable planning parameters that can provide insights into the social and economic returns on investment in specific interventions.

Figure 1 illustrates the stocks, flows, connectors, converters, and internal feedback loops of the SDM. Stocks represent the accumulation of goods and services over a specific period. In this study, stock denotes the number of animals at each successive stage of the reproductive cycle. Flow describes the rate of change in and out of stock and reflects the adjustment in the stock. In this study, flow represents the movement of the stock from one stage to another during the reproductive cycle. Several technical parameters and relationships govern the flow speed (inflow or outflow). These parameters and relationships are termed as converters. Converters provide information that influences the flow rates. They can represent the parameters or relationships that affect the system behavior. For instance, if the rate at which new animals are introduced into the herd (e.g., calves per year) is an inflow (which increases the stock of young animals), the

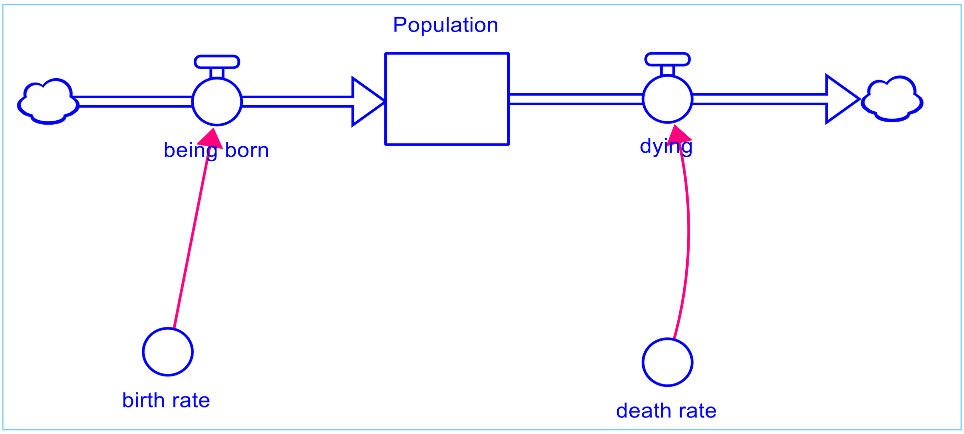
Figure 1. Components of system dynamic model



converter will be the fertility rate (percentage of breeding females that become pregnant each year). The converters for the model have been developed from data generated through interactions with experts and FGDs with livestock producers.

The concepts of stock, flow, and parameters are illustrated in Figure 2. Stocks (represented by rectangular shapes) are entities that accumulate or depreciate over time, such as the livestock population. The number of animals on a farm at a specific time exemplifies this stock concept. The stock fluctuates due to inflows or outflows (depicted as thick arrows), which are collectively termed "flows". For instance, the birth of new animals increases the population, whereas mortality decreases it. A parameter determines the rate at which flows occur; for example, the birth rate (percentage of births per annum) governs the rate of increase in the animal population.

Figure 2. Population stock and flow



This conceptual model can be expanded into a comprehensive system by delineating various stages of a species' life cycle through multiple parameters that influence the transition from one stage to another, as well as the rate at which progression occurs from one stage (stock) to the next. The flow of animals (parturient or those ready for slaughter) is projected for a specific improved germplasm utilizing the quantity of germplasm distributed and reproduction parameters. The flow of production (milk/ live body weight) is subsequently derived using production parameters. Employing the same quantity of germplasm, the flow of parturient animals/ animals for slaughter and production is also projected for the local germplasm. The projected figures for the improved and local germplasms are compared to determine the incremental benefits and costs, as well as the Net Present Value (NPV).

2.3 Model validation, assumptions and limitations

Model validation: It was performed in three complementary stages, following established SDM protocols (Sterman, 2000; Barlas, 1996).

(i) **Conceptual and structural validation:** The causal loop structure, parameter linkages, and equations representing reproduction, mortality, and production were reviewed by a multidisciplinary panel of subject matter experts from ICAR institutes (animal breeding, reproduction, extension, and livestock economics). The experts examined whether the model logic adequately captured herd and flock dynamics under Indian field conditions and whether the functional relationships and parameter ranges were biologically feasible. Adjustments were made when feedback loops oversimplified herd transitions (e.g., calving and replacement rates).

(ii) **Parameter and data validation (data reconciliation and cross-validation):** The primary data on production and reproduction parameters (e.g. age at first calving/parturition, inter-calving or inter-kidding interval, litter size, mortality rates) gathered through FGDs, were cross-checked against the long-term performance records maintained by the respective ICAR institutes. This ensured that the input parameters used in the model were consistent with empirical data from both field and research farm conditions.

(iii) **Behavioural and output validation (validation of supply projections):** The System Dynamics Model (SDM) serves as an ex-ante impact assessment tool to explore the potential economic and biological benefits of improved germplasm under idealized scenarios. Accordingly, output validation focused on ensuring the internal coherence, biological plausibility, and comparative integrity of projected supply trajectories.

The herd and flock dynamics, along with derived supply projections, were assessed to confirm that:

- Projection patterns were logically consistent with input biological parameters—for instance, shorter calving or kidding intervals, higher conception rates, and greater litter sizes appropriately translated into faster herd or flock expansion in improved germplasm relative to non-improved groups.
- The model avoided biologically impossible outcomes, such as negative populations, abrupt stock surges, or oscillatory instabilities that do not align with the reproductive biology of the species.

- The magnitude and direction of relative gains between improved and non-improved germplasm mirrored performance advantages observed in controlled breeding programmes and farm-based evaluations.

This approach—illustrating the upper bound of achievable gains under favorable biological parameters and management conditions—is consistent with established practice in ex-ante simulation modeling (e.g., Bystroff, 2021; Moritz et al., 2023), where the objective is to evaluate the potential impact of emerging technologies or interventions under unconstrained scenarios.

(iv) **Sensitivity and plausibility testing:** Key parameters, such as conception rate, mortality, feed cost, and output prices, were varied within realistic bounds (±20 per cent) to ensure that the model produced stable and biologically plausible outcomes (no unrealistic oscillations or negative populations). The results remained directionally consistent, implying the robustness of the projections.

Assumptions: SDMs are generally based on the assumption that the relationships between system elements can be described using cause-and-effect loops. These loops demonstrate how changes in one part of the system can influence the other. SDMs also incorporate time delays between causes and effects, recognizing that system responses to changes do not occur instantaneously. Regarding the application of the SDM in this study, it is assumed that the key variables influencing economic outcomes are the differences in performance between improved and traditional germplasms. This includes differences in productivity, reproductive efficiency, and other performance metrics that directly affect revenue and costs. The model assumes that the prices of inputs (such as feed and healthcare) and outputs (such as milk, meat, and eggs) remain constant over the projection period. It is also assumed that management practices remain consistent across the study period and do not differ significantly between farms using improved and traditional germplasms. The assumption of continuous flows helps to smooth the behavior of the model over time but may overlook sudden or unexpected changes. SDMs assume that the system boundaries are well defined and that interactions outside these boundaries have minimal or predictable impacts. This helps focus the model on the key dynamics but may ignore external factors that can significantly influence the system.

Scope and Limitations: The SDM used in this study simulates reproduction and productivity dynamics based on empirically grounded, species-and breed-specific parameters (e.g., age at sexual maturity, inter-parturition interval, and conception rate). As is standard in ex-ante modeling frameworks, the model operates under idealized biological and management conditions and does not incorporate dynamic feedback processes such as feed resource constraints, disease pressures, or adoption dynamics. Consequently, the projected population trajectories represent an upper-bound potential under favorable conditions, consistent with similar ex-ante SDM-based impact assessments (e.g., Moritz et al., 2023; Bystroff, 2021). The purpose of the model is to evaluate the relative economic benefits of improved germplasm, rather than forecast exact population outcomes.

2.4 Model structure

The overall model structure employed in this study is based on the specifications provided by Sterman (2000), and the general model structure is derived from Sterman (2002) and Lie et al. (2018), Mumba et al. (2017), and Dizyee et al. (2020). Appendix 2 provides maps of the models and illustrates the interconnections between the herd and modules (herd and breeding modules). Stocks represent different stages of maturation for kids/lambs/calves/piglets/chicks as they develop into adult females or males.

The modeling process begins with the annual distribution of germplasms, which serves as the foundation for tracking livestock population dynamics. This initial step is crucial for understanding the potential growth and sustainability of herds. As the model progresses, it meticulously tracks the flow of animals through various life stages, from birth to adulthood, for both females and males. This comprehensive approach allows for a detailed analysis of herd composition and growth patterns over time.

Throughout each stage of maturation, the model accounts for natural attrition and commercial sales, reflecting the real-world challenges and economic decisions faced by livestock managers. These factors significantly influence the herd's overall structure and productivity. The milk and meat modules are presented in Appendix 2. By calculating net revenue by subtracting costs from gross revenue, the model provides valuable insights into the economic impact of the improved germplasm, enabling stakeholders to make informed decisions regarding herd management, resource allocation, and long-term planning.

This study focuses on the economic impact of improved germplasms of cattle, goats, sheep, pigs, and poultry, and aims to understand how genetic improvements can influence the productivity and overall performance of different species. Furthermore, it provides a broad perspective on the potential benefits of improved germplasm technologies in diverse livestock production systems.

Species-specific SDM were developed to (Appendix 2) capture the unique characteristics and interactions within each livestock system. The corresponding system equations and parameters, which are crucial for understanding the dynamics and the quantitative aspects of the models are presented in Appendix 3. This structured approach allows for a systematic comparison of the impacts across different species, while accounting for their individual biological and production-related nuances. SDM enables the simulation of various scenarios and prediction of the long-term outcomes of germplasm improvements.

2.5 Cost-benefit analysis

The System Dynamics Model (SDM) simulation generated projections of livestock population growth, productivity improvements, and corresponding output flows over a 10-year period following the adoption of improved germplasm. To assess the economic feasibility of these interventions, a cost–benefit analysis was conducted for each germplasm, comparing the incremental benefits and costs accrued over the simulation horizon. The benefits were estimated as the additional returns realized owing to the improved productivity parameters attributable to the introduced germplasm. The total incremental benefit was computed as the difference between the projected output value from the improved germplasm and the traditional breeds. The incremental costs considered in the analysis primarily included the cost differentials of rearing improved germplasm over traditional counterparts.

Projections of population and output flow were made based on the AI/NS interventions made in the initial year, with benefits accruing over the subsequent 10-year period. The subsequent 10-year projections capture the biological and economic outcomes resulting from natural population expansion under enhanced reproductive parameters. While the model does not simulate repeated annual AI interventions, it reflects a 'founder population' strategy, where the traits of improved germplasm are retained through self-sustained herd growth, subject to reproduction constraints. This is consistent with assumptions that subsequent reproduction within the herd would propagate improved traits. The economic indicators used were NPV (calculated as the discounted sum of incremental benefits minus costs over 10 years) and Benefit–Cost (BC) ratio (computed as the ratio of total discounted benefits to total discounted costs.

Net Present Value: It measures the discounted value of incremental net benefits, i.e., the difference between the additional benefits and additional costs arising from the adoption of improved germplasm as compared to traditional or non-improved varieties.

$$NPV = \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} - \sum_{t=1}^{n} \frac{C_t}{(1+i)^t}$$

t = year
B_t = t_{th} year benefits
C_t = t_{th} year costs
i = discount rate considered at 5% per annum

A positive NPV indicates that the additional economic benefits from adopting improved germplasm exceed the additional costs over the assessment period, implying economic viability under the modelled conditions.

Benefit Cost Ratio: A BCR greater than 1 implies that the present value of incremental benefits exceeds that of incremental costs, making the adoption economically desirable.

$$BCR = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+i)^t}}$$

These indicators were calculated separately for each germplasm using the output data generated by the SDM. This approach allows for a forward-looking assessment of germplasm feasibility under dynamic herd evolution and biological performance assumptions.

It should be noted that breed development is a continuous, iterative process involving breeding, feeding, management, and other interventions, which are interlinked and often span a long period, making it challenging to accurately ascertain and allocate specific costs to the development of a particular breed. Accurate historical data on the costs of long-term breeding programs are scarce, and the economic evaluations in this study focused on the observable benefits derived from the adoption of improved germplasm, such as increased productivity and direct cost savings. Furthermore, this study provides an assessment of the economic gains that can be achieved through the adoption of improved germplasm, highlighting their feasibility and potential impact on profitability. Therefore, research and development costs were not included in this study.

3 Impacts of Improved Animal Germplasm

The following sections present the impact assessment of improved germplasm of different species. The modeling for each species is based on a comprehensive set of production and reproduction parameters, including lactation length, offspring per parturition, conception rates, and mortality, which are detailed in the accompanying tables. These parameters drive the projections for herd growth, total milk yield, and meat output, which are displayed in the subsequent figures and form the basis of the cost-benefit analysis.

3.1 Frieswal breed of cattle

India's dairy economy is predominantly cow-based. In 2022-23, India produced 239.30 million tons of milk, of which 54.68% was contributed by cows and 45.32% by buffaloes (GoI, 2024a). Approximately 11% of the total cow milk production is contributed by indigenous cows, and the remainder by crossbred cows. However, the milk yield of all dairy species is low. The average milk yield of an indigenous cow is 3.54 kg/day, and that of a crossbred cow is 8.43 kg/day (GoI, 2024a). These results highlight the need to improve dairy productivity through enhanced breeding and better management.

To address the challenges of low milk yield and adaptability to diverse climatic conditions, efforts have been made to develop specialized breeds, such as Frieswal, at the ICAR-Central Institute for Research on Cattle in Meerut, Uttar Pradesh, India. This breed, a cross between Holstein and Sahiwal cattle, demonstrates superior adaptability to various agroclimatic conditions while maintaining optimal reproductive parameters.

The Frieswal breed demonstrates several advantageous characteristics that set it apart from other cattle breeds, particularly in terms of reproduction and milk production (Table 1). Frieswal has 62.5% Holstein Friesian (HF) inheritance and 37.5% Sahiwal inheritance, with 10% variation. The performance of Frieswal has been compared with that of any other crossbred breed and has been referred to as 'non-Frieswal. 'Specifically, HF and Jersey cattle were chosen as comparators because they represent a significant portion of the crossbred cattle population in India and are often reared in similar agro-climatic conditions as the Frieswal breed. The shorter maturation period of Frieswal heifers (21–25 months) compared to that of other breeds (27–33 months) offers significant economic benefits to farmers. This reduced time to maturity not only lowers rearing costs but also allows rapid herd expansion, potentially leading to improved overall farm productivity and profitability. The breed's superior fertility is evident in its lower incidence of delayed conception and fewer AIs required per conception, further contributing to cost savings and increased life cycle productivity.

The inter-calving period is determined endogenously in the model based on the values of the gestation period, service period, and days open. Wide variations exist in service period (90-200 days and 120-220 days, respectively for Frieswal and non-Frieswal), although gestation period is the same for these. Accordingly, intercalving-period is shorter for Frieswal cattle (15-18 months) as compared to that of non-Frieswal cattle (18-20 months).

In addition to their reproductive advantages, Frieswal cows exhibit impressive milk production potential, with an average maximum milk yield of 28 liters/day, which is nearly double that of non-Frieswal cows. The reduced intercalving period by 2-3 months suggest that Frieswal cows can potentially produce more calves and milk over their lifespans. These characteristics, combined with lactation length, make Frieswal an important choice for dairy farmers.

Approximately 20,000 semen doses are used annually to inseminate breedable female Frieswal animals. Utilizing this as a foundation and other reproduction traits from Table 1, the populations of Frieswal and non-Frieswal cows were projected over a period of 10 years. Figure 3 presents the projected inflow into the stocks of in-milk Frieswal and non-Frieswal cows. The initial dissemination of 20,000 semen doses serves as a starting point for both Frieswal and non-Frieswal populations. The subsequent herd expansion over the 10-year period reflects natural reproduction under field conditions, with the growth driven by the reproductive efficiency of the germplasm. This approach enables a clear assessment of how improved traits (e.g., shorter calving interval and higher conception rate) translate into productivity and economic outcomes over time. The present analysis is designed to inform policymakers of the intrinsic performance advantage of Frieswal relative to other crossbreds, independent of external interventions.

The trend is analyzed on a daily basis for a period of 10 years (365 × 10 = 3650 observations). To accurately model the biological reality of dairy farming, the Frieswal cattle population and milk production were simulated on a daily time step. At the conclusion of the period, the number of lactating cows was estimated to be 1222 for Frieswal, compared to 356 for other breeds. The large difference in the projected number of lactating animals and total milk output is a direct result of the superior reproductive and productive traits of the Frieswal breed, as validated by our primary data. Key parameters from Table 1, such as a shorter inter-calving period, higher conception rate, and a significantly greater daily

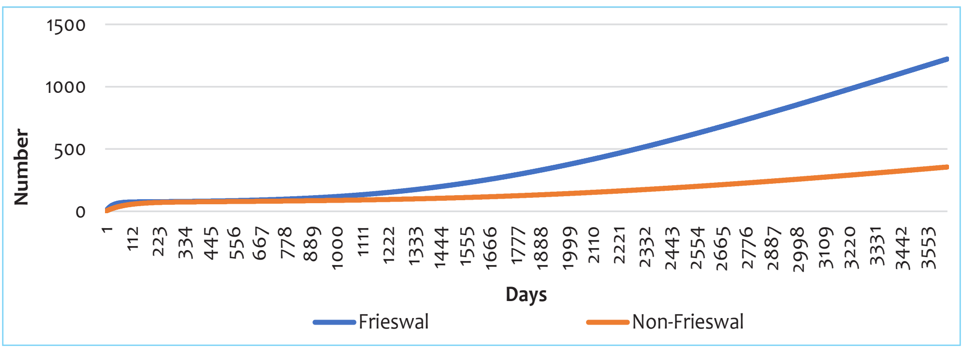
Table 1. Production and reproduction traits of Frieswal versus non-Frieswal cattle

Particulars	Frieswal	Non-Frieswal
For projecting calving/lactating animals		
Probability of being female	0.5	0.5
Age at sexual maturity (months)	16-18	18-19
Age at 1st calving (months)	30-34	36-42
Rearing period of heifer to breedable age (months)	21-25	27-33
Incidence of delayed conception (%)	30	50
Average number of days delayed on account of missed oestrus (days)	21	21
Average number of artificial inseminations (AIs) required per successful conception (No_AI)	1.5-2.0	3.5-4.5
Conception delay (days)	DD*((No_AI**-1) x DD	
Service period (days)	90-200	120-220
Gestation period (months)	9	9
Inter-calving period (months)	12-15.5	13-16.3
Probability of parturition (%)	0.95	0.95
Conception rate (%)	0.45-0.55	0.5
For projecting milk yield/production		
Lactation length (days)	300-360	240-270
Average maximum milk yield (liters/day)	28 (20-30)	15
Average minimum milk yield (liters/day)	12 (10-12)	08
Average lactation yield (liters) (Ali, 2011)	LL# x (Max_MY## + Min_MY###)/2	
Price of milk (Rs./kg)	35	

Source: Compiled by authors from FGDs with livestock farmers.
Note: *DD = Average number of days delayed on account of missed estrus
** No_AI = Average Number of AI required per successful conception
# LL = Lactation length (days)
Max_MY = Maximum daily milk yield
Min_MY = Minimum milk yield

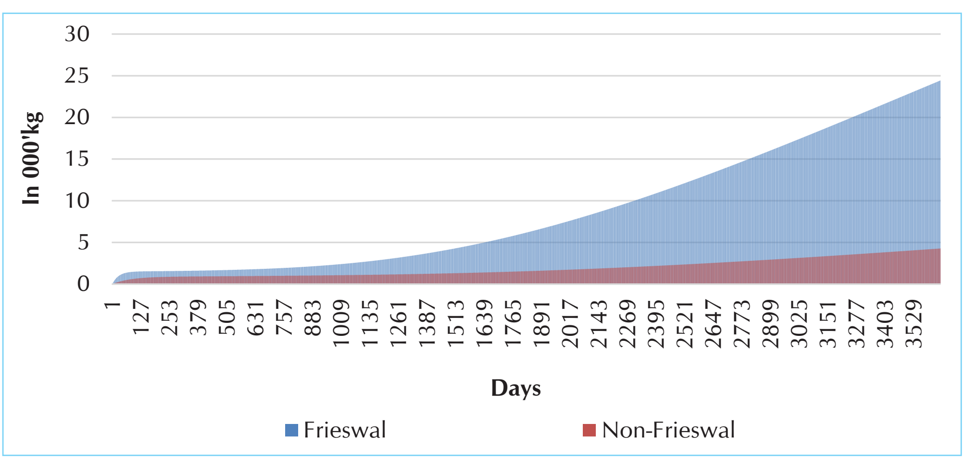
milk yield, compound over time within the SDM. This leads to faster herd growth and a substantially higher volume of milk production than non-Frieswal breeds under the same conditions. The SDM projects the total milk supply from the growing Frieswal herd over the 10-year period (Figure 4). At the end of the 10th year, the total milk production from the Frieswal herd is projected to be approximately 24 tons. This output was nearly six times greater than the projected daily production of the non-Frieswal cohort. This herd-level production is based on an estimated inflow of lactating animals yielding an average of ~20 liters per cow per day, a figure which is consistent with and validated by our FGD-based observed range of 15–28 liters/day.

Figure 3. Projected inflow into in-milk cow stock



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 4. Projected milk supply (in 000′ kg)



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Nonetheless, the cost difference between rearing Frieswal and local cows is significant, with Frieswal cows requiring 30% more (Table 2). This substantial difference is primarily attributed to the higher feed costs associated with the Frieswal cows. These crossbred animals typically have higher nutritional requirements.

Interestingly, although feed costs are higher for Frieswal cows, veterinary expenses are lower, perhaps because of the improved disease resistance and overall hardiness that Frieswal cows inherit from their Sahiwal lineage. The combination of Holstein Friesian (HF) genetics for high milk yield and Sahiwal genetics for adaptability to tropical conditions may have resulted in animals that are adaptable, less susceptible to common health issues, thereby reducing the frequency and cost of veterinary intervention as compared to other HF crossbreds (non-Frieswal). However, it is important to note that savings in veterinary expenses do not offset the higher feed costs, resulting in an overall higher annual rearing cost for Frieswal cows than for others. These cost figures are not modeled, but were collected through FGDs conducted with farmers managing Frieswal and non-Frieswal cattle in the study area and validated with expert opinion.

Table 2. Cost of rearing (Rs./cattle/annum)

Expenses	Frieswal	Non-Frieswal
Green fodder	43800	36500
Dry fodder	65700	32850
Concentrates	41975	32850
Veterinary expenses	4500	10000
Artificial insemination	150	350
Total cost	156125	112550

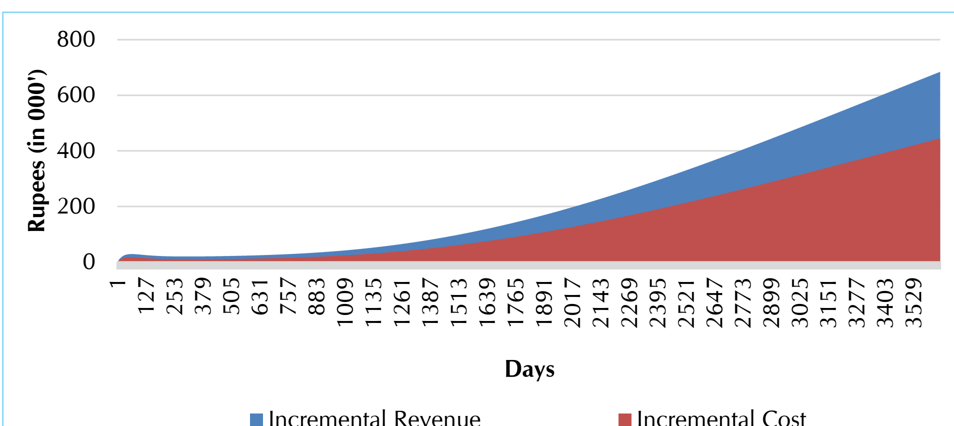
Source: Estimated by authors based on primary data from FGDs with farmers managing Frieswal and non-Frieswal cattle.

The values presented in Table 2 represent annual per-animal rearing costs under field conditions, based on farmer-reported expenditure during FGDs. These costs were held constant over the 10-year projection period in real terms to isolate and highlight the biological and economic advantages of improved germplasm over time. While the unit costs per animal remain unchanged in the model, the aggregate costs and revenues vary dynamically over the projection horizon due to differences in herd size, lactation dynamics, and output levels associated with each breed group. In terms of returns, the model calculates gross revenue endogenously for each year using the production parameters (milk yield, lactation length, etc.) and prevailing output prices (as given in Table 1). These are embedded directly in the model equations. The price-yield relationship is fully accounted for in the economic evaluation of each breed group.

Based on the projected population, milk sales, and rearing costs, the incremental returns and costs are presented in Figure 5. The values shown in Figure 5 represent incremental (net additional) costs and returns from rearing Frieswal cattle over and above the corresponding values for non-Frieswal (other crossbred) animals. The operational (recurring) costs and returns are compared. Thus, the incremental cost line reflects the extra expenditure attributable to the improved germplasm, whereas the incremental return line captures the additional revenue generated due to higher milk yield, better reproductive performance, and improved productive lifespan.

The economic assessment yields promising results, with an NPV of Rs. 61,650 million, indicating a substantial positive return on investment when considering the time value of money. Furthermore, the BC ratio of 1.57:1 suggests that for every rupee invested in the dairy sector, there is an expected return of Rs. 1.57.

Figure 5. Incremental costs and net revenue for Frieswal cattle (in 000' Rs.)



3.2 Barbari breed of goat

The goat population in India is estimated to be 149 million. In 2023-24, goats produced 7.8 million tons of milk, accounting for 3.36% of the total milk production, and 1.61 million tons of meat, constituting

15.50% of the total meat production (GoI, 2024a). India's goat genetic diversity is remarkable, with 41 recognized breeds. However, of the total goat population, 27.4% represents pure breeds, 9.1% graded breeds, and the remaining majority being non-descript.

Among these breeds, Barbari goats are notable examples of adaptation and productivity. This small-sized dual-purpose (meat and milk) breed is primarily found in the northwestern arid and semi-arid regions of India, particularly in the districts of Agra, Aligarh, Etah, Etawah, Hathras, and Mathura in Uttar Pradesh, as well as the Bharatpur district in Rajasthan. The Barbari breed is characterized by high prolificacy and non-seasonal breeding patterns, making it well-suited for rearing under confined and stall-fed conditions. These traits, along with their ability to adapt to extreme heat, result from long-term evolutionary processes and environmental interactions. The Barbari goat's unique characteristics and adaptability make it a valuable asset in India's diverse goat genetic resources. The performance of Barbari has been compared with non-descript local goat breeds in Uttar Pradesh which have been referred to as 'non-Barbari'.

Tables 3 and 4 present the reproduction and production parameters used to model the impact of Barbari. The Barbari breed demonstrates superior reproductive and production characteristics compared with non-Barbari breeds, as evidenced by data from the Central Institute for Research on Goats and FGDs. Barbari goats reach sexual maturity earlier (9-12 months) than non-Barbari goats (11-12 months), with a shorter age at first parturition (14.5 months vs. 16 months). This breed also exhibits higher reproductive efficiency, with a kidding rate of 2.11 per annum and significantly higher twinning rates (35-45% initially, 70-75% subsequently) than other breeds (20-30% initially, 40-45% thereafter). In addition, the Barbari breed requires fewer services per conception and has a shorter service period, contributing to their overall enhanced productivity.

Barbari breed shows superior performance in terms of production parameters. They have lower mortality rates, particularly in animals less than one year of age (5-8% vs. 12-20% in non-Barbari breeds). The breed also shows improved growth rates, with higher six-month body weights that persist in the juvenile stage. The average weight of Barbari goats (21.97 kg) is notably higher than that of the non-Barbari goats (18.11 kg). These factors, combined with their reproductive advantages, contribute to the higher life cycle productivity of the Barbari breed.

Table 3. Reproduction traits of Barbari versus non-Barbari goats

Parameter	Barbari	Non-Barbari/local
Probability of being female	0.5	0.5
Age at first breeding (months)	9-12	11-12
Age at 1st kidding (months)	14.5	16
Inter-kidding interval (months)	8-9	8-9
Number of kidding/annum	2.11	2.00
Twinning % (1st parturition)	35-45	20-30
Twinning % (Rt rest parturitions)	70-75	40-45
Number of kids born per parturition	1.5-1.8	1.2-1.4
Average number of services required per conception	1.2	1.3
Average number of days delayed on account of missed oestrus	20-30	25-35
Service period (days)	70-90	90-110
Gestation period (days)	144-150	144-150
Probability of parturition / kidding rate (%)	88-95	82-90
Conception rate (%)	85-90	70-80
Mortality up to 1 year (%)	5-8	10-20
Mortality > 1 year (%)	4-8	6-15

Source: Estimated by authors based on primary data from FGDs with farmers.

Live weight produced (in kg) per female at birth is 22.4 kg (2 kg/kid × 7 kidding/lifetime × 1.6 kids/kidding). Furthermore, the live weight at 45 days (in kg) per female is 208 kg (19.5 kg/kid × 7 kidding/lifetime × 1.6 kids/kidding), and the live weight produced (in kg) per female at slaughter is 297 kg (26.5 kg/kid × 7 kidding/lifetime × 1.6 kids/kidding).

Table 4. Production parameters of Barbari versus non-Barbari goats

Parameter	Barbari	Non-Barbari/local
Body weight at 6 months	12-13	9-12
Body weight at 9 months	17-22	14-17
Body weight at 12 months	23-30	18-26
Average live body weight	21.97	18.11
Dressing (%)	48-53	45-50
Price of goat meat fresh (Rs./kg)	600	600

Source: Estimated by authors based on primary data from FGDs with farmers.

Based on the germplasm information provided in Table 5, a total of 37,800 breedable Barbari goats are utilized in the initial year. Using the reproductive parameters outlined in Tables 3, and 4, for both Barbari and non-Barbari goats, the study projects a remarkable growth in the Barbari goat population over a decade. The results show that the offtake of Barbari goats after ten years is approximately three times higher than that of non-Barbari goats, as illustrated in Figure 6.

The projected number of goats available for sale remains similar for both improved (Barbari) and non-Barbari goats during the initial years because the first production cycles are driven by the same founding stock size and gestation period. Divergence becomes visible from the sixth year onward as the compounding effects of a higher kidding rate, shorter inter-kidding interval, lower mortality, and faster growth rate in Barbari goats begin to accumulate across successive populations.

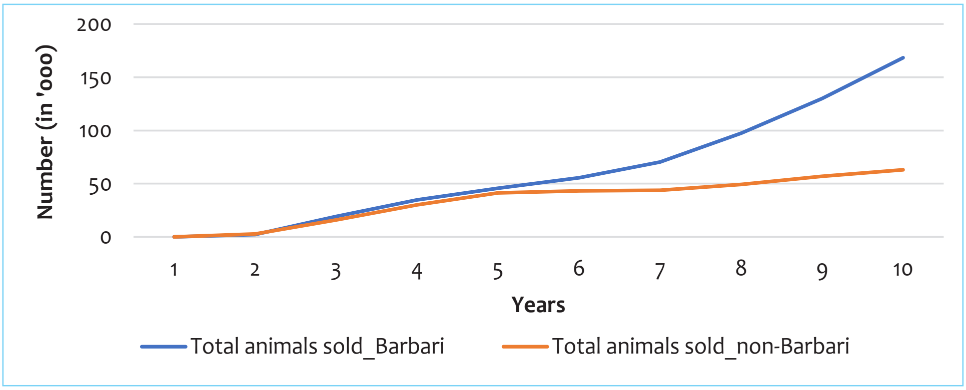
Further analysis reveals the potential impact on meat production. By considering the average dressing percentage provided in Table 4 and the live body weights of both Barbari and non-Barbari goats, the study estimates a significant difference in meat production between the two breeds by the end of the 10-year period. The projected meat production from Barbari goats is estimated at 2250 tons, while non-Barbari goats are expected to produce 784 tons (Figure 7). The temporary reduction in Barbari meat production in Year 4, despite similar sale numbers, is due to a shift in the age and sex composition of animals sold in that year. The model allocates a larger share of female kids to herd replacement in year 4, resulting in a higher proportion of lighter, younger males entering offtake than in year 3. Since meat output is calculated as *(number sold × average liveweight × dressing %)*, this change in sale weight leads to a short-term dip in total meat production, even though herd size remains comparable. From the fifth year onward, once the replacement stabilizes, the cumulative reproductive advantage of Barbari results in consistently higher meat output.

Table 5. Baseline assumptions (no. of breedable female goats served)

Particulars	Values
Number of semen doses disseminated	6000
Number of germplasm distributed	1000
Share of bucks in distributed germplasm	70%
Services per buck per annum	45
Total natural services + artificial inseminations (i.e. No. of breedable animals served in the initial year)	37800

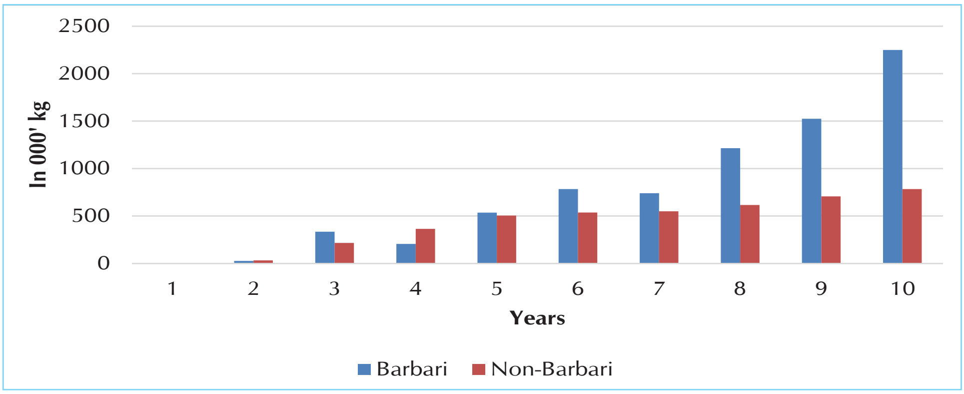
Source: Authors' compilation from expert inputs and institutional records.

Figure 6. Projected number of goats for sale



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 7. Projected goat meat supply (in 000' kg)



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

However, rearing the Barbari breed also incurs higher expenses (Table 6), approximately 1.2 times the cost of rearing non-Barbari breeds. The primary cost drivers for both Barbari and non-Barbari goats are feeding and grazing. However, the balance between these two factors varies greatly. Barbari breed requires less grazing time, typically 4-5 hours daily for 280-300 days per year, which results in lower grazing expenses. However, this reduced grazing is offset by higher feed costs, suggesting that Barbari goats may require more supplementary nutrition to meet their dietary requirements.

The contrasting management approach for non-Barbari goats involves more extensive grazing, with 5-7 hours spent daily over a longer annual period of 300-350 days. This extended grazing time likely contributes to lower feed costs for non-Barbari breeds, as they obtain more of their nutritional requirements directly from pastures. The trade-off between grazing time and feed costs highlights the importance of considering local resources, labor availability, and market conditions when choosing between Barbari and non-Barbari breeds.

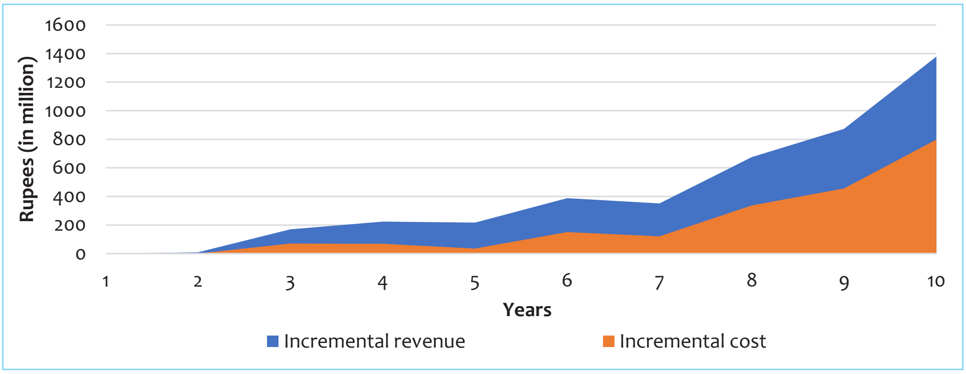
Table 6. Cost of rearing (Rs./goat/annum)

Expenses	Barbari	Non-Barbari
Feed	4009	2200
Veterinary charges	75	90
Miscellaneous	45	70
Grazing (hrs/day)	4-5	5-7
Grazing duration (days/year)	280-300	300-350
Grazing expenses	1631	2438
Total expenses	5760	4798

Source: Estimated by authors based on primary data from FGDs with farmers.

Based on the projected population, the incremental benefits from Barbari germplasm have been estimated (Figure 8). The decline in incremental costs and net revenue observed in years 5 and 7 reflects the cyclical dynamics of the herd structure. In these years, a higher proportion of Barbari goats, especially female kids, are retained for breeding and replacement, which temporarily reduces the number of heavier, sale-ready animals. Correspondingly, the cost per sold animal declines due to lower marketing and feeding expenditures, while total revenues decrease due to lower sale weights or fewer surplus males entering the market. This short-term fluctuation is typical of herd expansion phases

Figure 8. Incremental cost and net revenue from adoption of Barbari goats (in Rs. million)



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

in improved germplasm and stabilizes once replacement requirements are met, after which incremental gains from Barbari become consistently higher.

With an estimated NPV of Rs. 1570.7 million and a BC ratio of 2.13:1, Barbari goat farming has emerged as a financially attractive option. This high BC ratio indicates that for every rupee invested in Barbari goat farming, farmers can expect a return of 2.13 rupees, demonstrating a substantial profit margin. These findings align with those of Prasad et al. (2013), who reported a higher BC ratio for Barbari goats (1.70) than for non-descript goats (1.53).

3.3 Avishan-a triple crossbred sheep

India has an estimated 74.26 million sheep, producing 1.14 million tons of mutton, which accounts for 11.13% of the total meat production (GoI, 2024a). There are 44 registered sheep breeds in India. Of the total sheep population, 5.51% belongs to exotic/crossbred, 43.90% are pure/graded breeds, and 50.60% are non-descript (Appendix 1).

Avishan, a triple cross (Malpura–25%; Garole–25%; Patanwadi–50%), demonstrates superior traits, such as high prolificacy, increased litter weight, and enhanced meat yield. Its adaptability to various climatic conditions, from arid to temperate zones, makes it a versatile option for farmers across different geographical regions in India. High fertility rates, resulting in frequent twin or triplet births, coupled with accelerated lamb growth, contribute to improved overall productivity and economic returns for sheep farmers. Demonstration units of Avishan sheep have been established in Rajasthan with the help of the state government, and ICAR-CSWRI, Avikanagar, has also supplied Avishan sheep units to farmers.

Tables 7 and 8 present the reproduction and production parameters used to estimate the system dynamic model. This genotype attains breeding age at 370 days, 30 days earlier than non-Avishan breeds, indicating an earlier onset of reproductive maturity and a potentially extended productive lifespan. The non-Avishan breed refers to Malpura, a prominent breed of sheep prevalent in Rajasthan. The Avishan sheep breed demonstrates superior reproductive characteristics compared to non-Avishan breeds, making it a valuable asset for sheep farming and breeding programs. The earlier attainment of breeding in this breed allows for a longer productive lifespan and potentially more breeding cycles over the lifetime. This, coupled with a shorter interlambing interval of 11.5 months, enables Avishan sheep to produce lambs more frequently, thereby increasing the overall flock productivity. The breed's genetic predisposition for multiple births, evidenced by a significantly higher twinning rate and an average of 1.8 lambs per parturition, further enhances reproductive efficiency.

The shorter service period of 197 days for Avishan results in quicker returns. The higher conception rate of 95% suggests that breeding efforts with Avishan sheep are more likely to be successful, reducing resource wastage. Additionally, the breed's larger average live body weight, with males being 4.2 kg heavier and females 1 kg heavier than other breeds, may contribute to better overall health and potentially higher quality meat production.

The same number of breedable animals served for the Avishan and non-Avishan breeds is utilized in the model to project the herd structure over a period of 10 years using the reproduction and production parameters presented in Tables 7 and 8. Table 9 shows the germplasm disseminated by the ICAR-CSWRI. The total number of breedable animals served has been estimated at 39,990.

Figure 9 illustrates the projected population dynamics of Avishan and non-Avishan/local sheep breeds over a specified period. There is a significant difference in the number of sheep sales of the two groups, with Avishan sheep sales surpassing those of other breeds by approximately 1.4 times at the end of ten years. The higher sale numbers for non-Avishan in years 4–5 arise from lower replacement retention in those years (fewer ewe-lambs held back), so more animals enter offtake despite similar base stocks. In contrast, Avishan retains a larger share of females to expand the breeding base, delaying sales. The common dip in year 6 reflects a biological lag—animals retained for replacement in the preceding cycle reduce saleable surplus one cycle later, producing a temporary trough before the numbers rise again. This pattern is a standard herd-flow effect driven by inter-lambing intervals, retention priorities, and age at sale.

The study further projects meat supply from both Avishan and non-Avishan breeds, as shown in Figure 10. These projections are based on the average dressing percentage (detailed in Table 8) and live body weight of the animals. Live weight produced (in kg) per female at birth was 30.87 kg (2.45 kg/lamb × 7 lambing/lifetime × 1.8 lambs/lambing). Further, live weight weaned at 45 days (in kg) per female is 167 kg (13.29 kg/ lamb × 7 lambing/ lifetime

× 1.8 lamb/lambing); and live weight produced (in kg) per female at slaughter is 299 Kg (23.75 kg/ lamb × 7 lambing/ lifetime × 1.8 lamb/lambing).[1]

The estimates indicate that Avishan sheep are expected to yield 896 tons of meat, whereas other breeds are projected to produce 702 tons of meat. However, it is worth noting that the rearing costs for Avishan sheep are marginally higher than those for other breeds, as presented in Table 10.

Table 7. Reproduction traits of Avishan versus non-Avishan sheep

Parameters	Avishan	Non-Avishan
Probability of being female	50%	50%
Age at first breeding (days)	370 days	400 days
Age at 1st lambing (months)	18	18.50
Inter-lambing interval (months)	11.5	12
No. of lambing/annum	01	01
Twinning % (1st parturition)	61	02
Twinning % (rest parturitions)	70	04
Number of lambs born per parturition	1.80	1.08
Average number of days delayed on account of missed oestrus (days)	18-20	18-20
Average number of services required per conception (No_AI)	1.30	1.30
Conception delay (days)	DD*(No_AI**-1) XDD	
Service period (days)	197	215
Gestation period (days)	150	150
Probability of parturition / lambing rate (%)	-	-
Conception rate (%)	95	90
Mortality up to 1 year (%)	04-05	02-2.5
Mortality > 1 year (%)	2.0	2.0

Source: Estimated by authors based on primary data from FGDs with farmers.
Note:* DD = Average number of days delayed on account of missed estrus
** No_AI = Average Number of services required per successful conception

Table 8. Production parameters of Avishan versus non-Avishan sheep

Parameters	Avishan		Non-Avishan	
	Male	Female	Male	Female
Body weight at 6 months	25.80	21.94	27.18	24.21
Body weight at 9 months	-	-	30.78	26.00
Body weight at 12 months	37.04	29.18	35.41	29.48
Average live body weight	47.20	35.00	43.00	34.00
Price of fresh meat (Rs./kg)	600		600	
Dressing %	50		50	

Source: Estimated by authors based on primary data from FGDs with farmers.

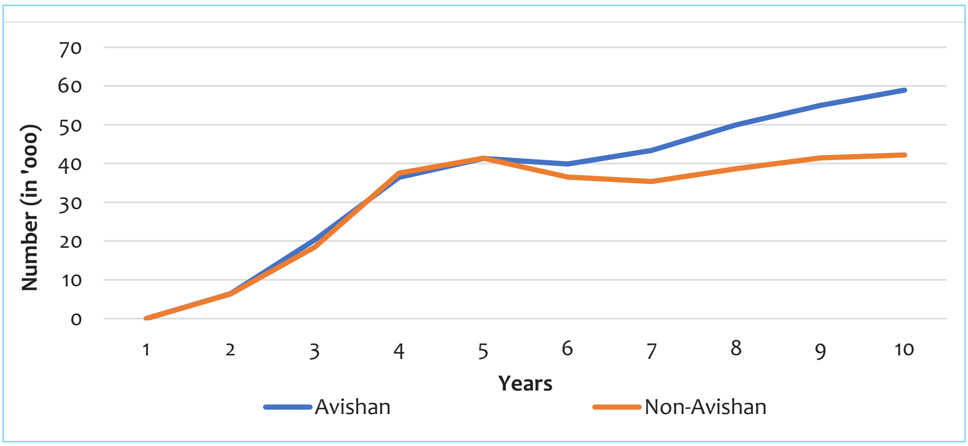
[1]For Avishan sheep, inter-se mating started in 2010, and the 7th generation is still running.

Table 9. Baseline assumptions (no. of breedable female sheep served)

Particulars	Values
No. of semen doses disseminated by CSWRI last year	-
No. of germplasm distributed	744
Share of bucks in germplasm disseminated	43%
Services per ram per annum at field level	125
Total natural services + artificial inseminations (i.e. No. of breedable animals served in the initial year)	39990

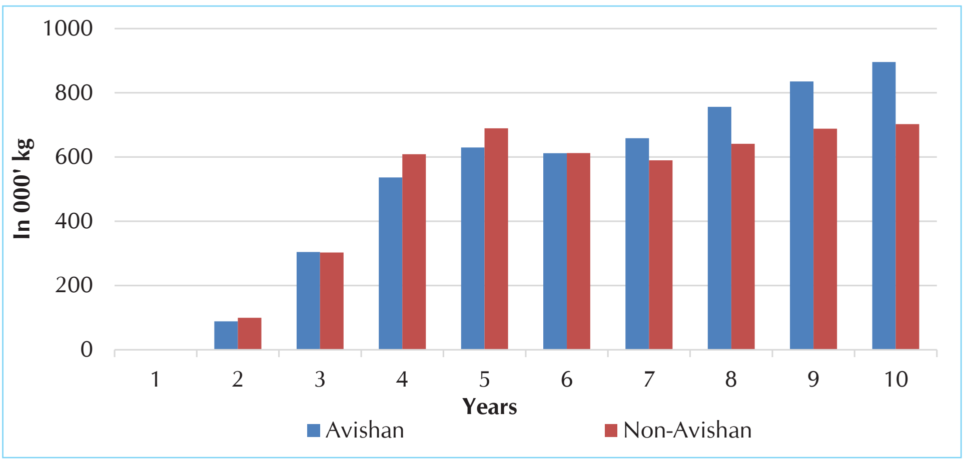
Source: Authors' compilation from expert inputs and institutional records.

Figure 9. Projected number of sheep for sale



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 10. Projected sheep meat supply (000' kg)



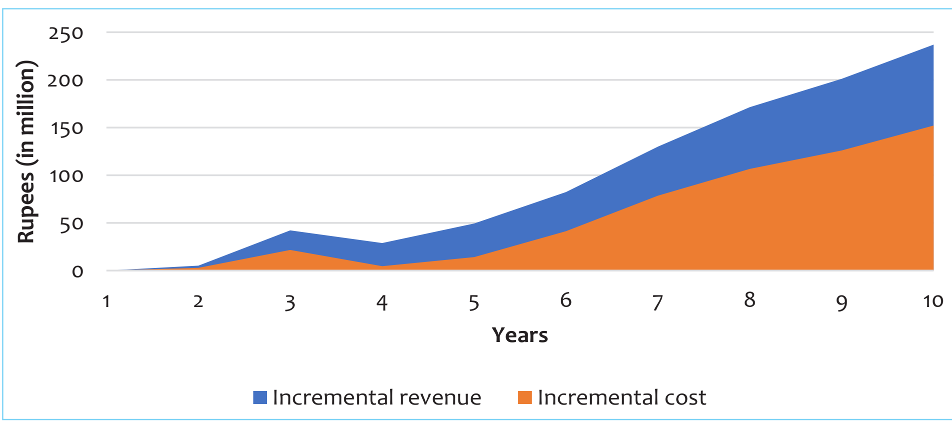
Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Table 10. Cost of rearing (Rs./sheep/annum)

Particulars	Avishan	Non-Avishan
Feed cost	18.25	17.75
Veterinary cost	108	100
Miscellaneous expenditure	40	40
Grazing (hrs/day)	6	6
Duration (days/year)	-	-
Grazing expenses	1440	1260
Cost of natural services	100	100
Total expenses	8158	7790

Source: Estimated by authors based on primary data from FGDs with farmers.

Figure 11. Incremental cost and net revenue from adoption of Avishan sheep (in Rs. million)



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

The economic analysis of the Avishan sheep breed reveals promising results even in harsh climatic conditions. Projections that consider both population dynamics and financial aspects provide a comprehensive view of the potential benefits of improved germplasm. The Avishan breed demonstrates a significantly positive return on investment, with an NPV of Rs. 278.9 million. Additionally, the benefit-cost ratio of 1.76:1 suggests that for every rupee invested in Avishan sheep farming, there is a return of Rs. 1.76.

3.4 Rani-a crossbred variety of pig

India has 9.05 million pigs. These produce 0.38 million tons of pork, accounting for 3.72% of the total meat production (GoI, 2024a). There are 14 registered pig breeds in India. Approximately 79% of the pigs are indigenous and non-descript, and most of these are yet to be characterized (Appendix 1). Owing to the poor performance of indigenous pigs, exotic pigs have been introduced, and the crossbreeding of native pigs with exotic boars has gained momentum.

Rani, a crossbreed of the Ghungroo and Hampshire breeds developed by the ICAR-National Research Centre on Pig, Guwahati, Assam, represents a significant advancement in pig breeding in north-eastern India. The Rani breed has several key characteristics, including enhanced weight gain, improved reproductive performance, and superior feed conversion efficiency. These traits have been rigorously validated across multiple states in north-east India, confirming their adaptability and performance under various local conditions. The selection of breeds for developing the Rani breed was based on their superior growth rate, reproductive efficiency, adaptability, and lean-meat production. The Hampshire (exotic) and Ghungroo (indigenous) breeds were chosen because of their complementary traits: Hampshire for its rapid growth, high feed efficiency, and lean meat yield, and Ghungroo for its larger litter size, better adaptability, and moderate growth performance.

The accelerated growth rate of the Rani breed sets it apart from its local counterparts, allowing it to reach a marketable weight significantly faster. This rapid growth has profound implications for pig farmers, as it enables them to shorten the production cycle and bring their livestock to market at a younger age. Furthermore, the Rani breed boasts a favorable meat-to-bone ratio and higher body weight, which are highly valued in commercial pig production.

The spread of Rani has been facilitated through organized multi-location trials and extensive field-level distributions. The variety has been successfully tested in different states, including Assam, Nagaland, Manipur, and Meghalaya, where it has demonstrated superior performance in terms of growth, reproduction, and adaptability. The institute has distributed a large number of germplasms to different parts of Assam, Meghalaya, and West Bengal. The Mega Seed Project on Pig Centre in Nagaland and the All India Coordinated Research Project (AICRP) on Pig Centre in Manipur has played a crucial role in distributing this improved germplasm to farmers in Nagaland and Manipur.

'Non-Rani' refers to local breeds that are commonly found in the regions studied, specifically Doom, Ninag Megha, and other locally available non-descript animals. These breeds were chosen as comparators because they represent a significant portion of the pig population in the area and are often used in similar agro-climatic conditions as the Rani pig. Tables 11 and 12 present the reproduction and production parameters of Rani vis-à-vis other breeds used to assess the economic impact of the adoption of Rani. The Rani breed demonstrates remarkable reproductive and growth characteristics that distinguish it from other breeds. Its early sexual maturity, occurring at 6.5-7.5 months compared to 7.5-9 months in other breeds, coupled with a shorter interval between farrowings (5-5.5 months versus 10-13 months), allows for more frequent reproductive cycles. This accelerated reproductive timeline, combined with larger litter sizes of 10-15 piglets (compared to 3-11 in other breeds) and an extended reproductive lifespan, results in a significantly higher lifetime offspring production of 35-40 piglets, far surpassing the 13-18 offspring typical of other breeds. The superior conception and farrowing rates of the Rani breed further contribute to its reproductive efficiency.

In terms of growth, the Rani breed consistently outperforms the other breeds at all developmental stages. By 8 months of age, Rani pigs reach an average weight of 85 kg, nearly double that of other breeds. The breed's reliance on AIs (85-90%) allows for precise genetic selection, potentially contributing to these superior traits.Although specific feed conversion efficiency data are unavailable, the accelerated growth rates and larger body sizes suggest that Rani pigs exhibit better feed utilization. Live weight produced (in kg) per female at birth is 40-45 kg (0.9 kg/piglet × 3 to 4 farrowing/lifetime × 10 to 15 piglet/farrowing). Furthermore, live weight weaned at 40-45 days (in kg) per female is 300-340 kg (9 kg/piglet × 3 to 4 farrowing/lifetime × 9 to 13 piglet/farrowing, considering a pre-weaning mortality rate of 5-10%), and live weight produced (in kg) per female at slaughter (8 months of slaughter age) is 2800-3200 kg (85 kg/piglet × 3 to 4 farrowing/lifetime × 8 to 12 piglet/farrowing, considering a post-weaning mortality rate of 5%). The Rani breed has completed more than 10 generations of inter-se-mating on the Institute farm, and all the production and reproduction parameters are well stabilized.

Population growth and meat production projections from the Rani breed over a 10-year period demonstrate its potential as a valuable livestock resource. Based on the number of disseminated germplasms and AIs performed by the ICAR-NRCP, the Rani breed is expected to experience a substantial increase in population, with a 75% increase in sales by the end of the decade.

Table 11. Reproduction traits of pigs (Rani versus other breeds)

Parameters	Values	
	Rani	Non-Rani
Probability of being female	0.5	0.5
Age at sexual maturity (months)	6.5-7.5	7.5-9
Age at 1st farrowing (months)	10-10.5	11-12
Inter-farrowing interval (months)	5-5.5	10-13
Average number of services required per conception	1-1.2	1.5
Average number of days delayed on account of missed oestrus (days)	20-22	20-22
Service period (days)	65	85
Gestation period (days)	110-120	104-114
Probability of parturition / farrowing rate (%)	0.95	0.70-0.75
Conception rate (%)	75	70
No. of piglets born per farrowing	10-15	3-11
Number of parturitions per reproductive female in its life time (reproductive period of a breedable female) (years)	3-4	2-3
Number of off springs born alive per reproductive female in its life time	35-40	13-18
Breeding method at field level (NS/AI)	85-90 (AI)	100 (NS)
No of AIs per annum	10000	

Source: Estimated by authors based on primary data from Focus Group Discussions with farmers.

Table 12. Production parameters of pigs (Rani versus other breeds)

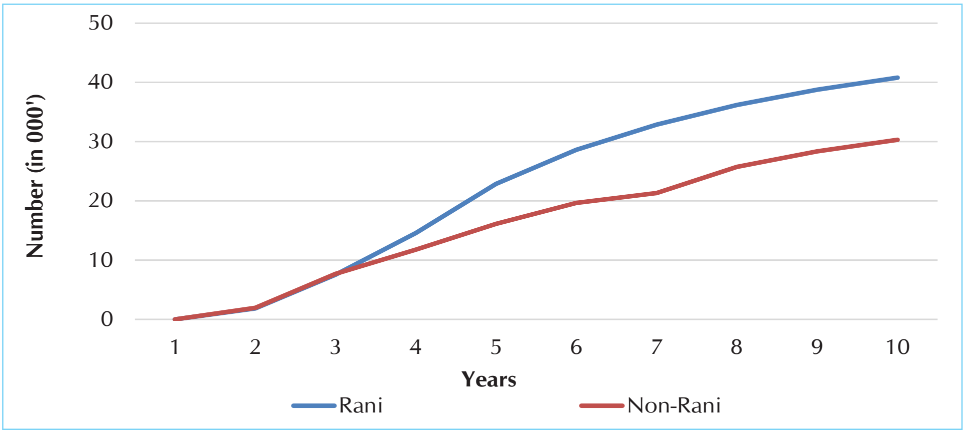
Particulars	Rani	Non-Rani/Local
Piglets average weight (up to 1.5 months) (kg)	9.0	5.0
Young animals average weight (up to 4-5 months) (kg)	40.0	22.0
Finisher average weight (at 8 months) (kg)	85.0	45.0
Sow for breeding purpose weight (kg)	130.0	52.0
Boar for breeding purpose average weight (kg)	150.0	55.0
Dressing (%)	73-75	73-75
Price of fresh pig meat (Rs.)	400	400

Source: Estimated by authors based on primary data from FGDs with farmers.

Furthermore, with an estimated 2367 tons of meat, the Rani variety produces three times more meat than the other breeds by the end of the 10^{th} year. This significant difference can be attributed to the higher average dressing percentage and live body weight of Rani.

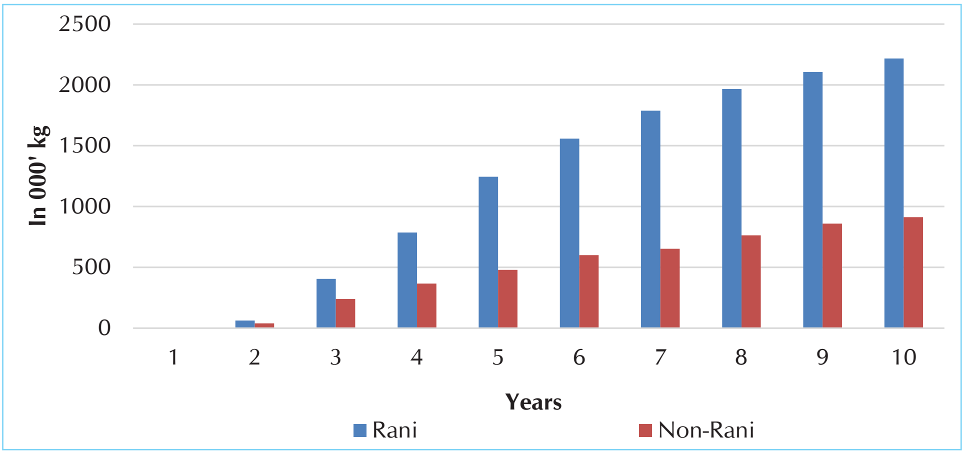
However, it is important to note that increased productivity comes at a cost, as the Rani breed requires more feed, making its rearing more expensive than that of other breeds. This trade-off between higher meat yield and increased production costs is an important consideration for farmers.

Figure 12. Projected number of pigs for sale



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 13. Projected supply of pig meat (000' kg)



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

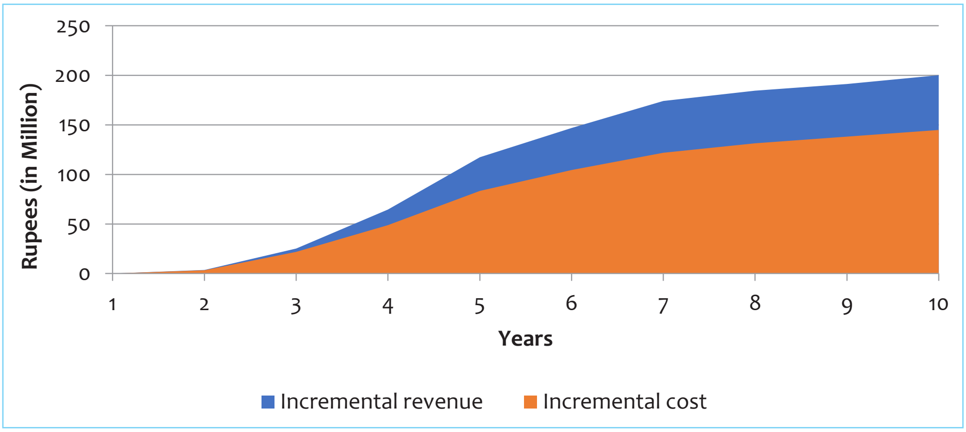
Based on the projected population, the estimated incremental returns and costs are presented in Figure 14. Despite the higher initial costs, including feed costs, the incremental return from Rani is substantially larger. This is evidenced by the substantial NPV of Rs. 215.2 million. The BC ratio shows that for every rupee invested, breeding could generate 1.59 rupees in returns.

Table 13. Feed requirement of Rani and other pig breeds

Rani	Duration (in months) for which concentrate is fed	Concentrate required/ day (kg)	Local feed required/ day (kg)	Non-Rani/ local	Duration (in months) for which concentrate is fed	Concentrate required/day (kg)	Local feed required/ day (kg)
Starter (up to 1.5 months)	1.5 months	0.125	0.125	Starter (up to 1.5 months)	1.5 months	0.10	0.10
Grower (1.5-6 month	4.5 months	0.25	0.25	Grower (1.5-6 month	4.5 months	0.2	0.20
Finisher (6-8 month)	2 months	1.0	1.0	Finisher (6-8 month)	2 months	0.5	1.0
Gilt	4 months (8m to 1 yr)	1.0	1.0	Gilt	4 months (8m to 1 yr)	0.5	1.0
Sow / Nursing sow	24 months (1 yr to 3 yrs)	1.25	1.25	Sow/ Nursing sow	24 months (1 yr to 3 yrs)	0.5	1.0
Boar	32 months (8m to 3.5 yrs)	1.50	1.50	Boar	32 months (8m to 3.5 yrs)	0.5	2.0

Source: Authors' compilation from expert inputs and institutional records.

Figure 14. Incremental cost and net revenue from the adoption of Rani pig (in Rs. million)



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

3.5 Gramapriya and Vanaraja poultry varieties

India's poultry sector is characterized by a dualistic structure, with the concurrent presence of a highly organized commercial sector and an unorganized traditional backyard sector. Approximately 37% of poultry are maintained under the backyard system, with chickens constituting approximately 89%. Notably, 81% of the chickens in the backyard poultry are of indigenous origin. There are 21 recognized native chicken varieties. These indigenous varieties are often well-suited to local climates and are resistant to regional diseases, making them invaluable assets for small-scale farmers. Moreover, backyard poultry serves as a vital source of nutrition for socio-economically disadvantaged communities, providing easily accessible protein through meat and eggs.

Vanaraja and Gramapriya are two improved poultry varieties that have gained significant importance in backyard farming in India. These varieties have been specifically developed to enhance livelihood opportunities and improve nutritional status. Vanaraja, a dual-purpose variety, is renowned for its adaptability to diverse climatic conditions and enhanced immune competence, making it ideal for free-range farming. Males are suitable for meat production at approximately 12 weeks of age, whereas females start laying eggs from 24 weeks of age. This versatility has contributed to its widespread acceptance. In contrast, Gramapriya is a layer-type variety that excels in scavenging conditions and free range environments. This variety is particularly valued for its high egg production, which contributes to improved egg production in backyard settings and is produced by crossing exotic with local birds for better adaptation and higher productivity.

Presently, Vanaraja and Gramapriya varieties are present from the Andaman and Nicobar Islands to Ladakh, across all the north-eastern states and other states of the country. ICAR-DPR is the main sources of supply of parent line in almost all the states through All India Coordinated Project on Poultry Breeding, Poultry Seed Project, State Agricultural/ Veterinary University, Krishi Vigyan Kendras and State Animal Husbandry Department.

Table 14 presents the reproductive and productive performance of the improved poultry varieties, Vanaraja and Gramapriya, relative to the non-descript indigenous birds commonly reared in rural backyard systems.

These local birds are not formally characterized as varieties and are often of mixed lineage owing to uncontrolled natural mating under low-input production systems. Thus, they serve as a relevant baseline for assessing the incremental benefits of the Vanaraja and Gramapriya varieties.

Table 14. Production and reproduction traits for poultry varieties

Parameters	Vanaraja	Gramapriya	Local
Eggs laid by breeding/parent stock (lifetime)	210	240	60-80
Maximum no. of chicks produced	120	140	50
Proportion of eggs laid by breeding/parent stock used for breeding (%)		100	
Hatching rate of eggs used for breeding purpose (%)	75	75	60
Hatching time (days)		21	
Maturity time (age of sexual maturity of birds) (weeks) Start egg laying – Parent stocks (weeks)	22-25	21-23	27-30
Commercial	20-23	20-22	27-30
Time for slaughter (approximate time from reaching stage for sales and actual slaughter)-for male (months)	3-4	4	6-12
Breeding/Parent stock productive life (weeks)	64-72	64-72	72
Mortality rate (%) of chicks (including weather stress/predator attacks/disease incidence)	15	15	10-20
Mortality (%) overall (at field level)	20-30	20-30	10-20
Price of fresh meat (per kg)-live body weight (Rs.)	200-400	200-400	350-600
Weight of male at market age	1.5-1.8 kg at 3 months	1.5-1.8 kg at 4 months	1.5-2 kg at 6 months
Price of egg (per unit) at field level (Rs.)	5-15	5-15	5-10
Egg production /birds	100-120	160-180	60-80
Price of spent birds (after egg production) (Rs.)	200-300	200-300	150-250
Price of one live bird belonging to parent stock/line (Rs.)	Chicks- Female: 100 Male: 50 Ratio- 5:1	Chicks- Female: 90 Male: 45 Ratio- 5:1	30-50
Cost of rearing one poultry bird (lifetime) (Rs.)			
i. vaccination/treatment	10	10	0-10
ii. labour	--	--	--
iii. feed (for small farmers)	150-250	300	200
iv. chicks	19	17	30-50
Dressing (%)	71-76	70-72	72-75

Source: Estimated by authors based on primary data from FGDs with farmers.

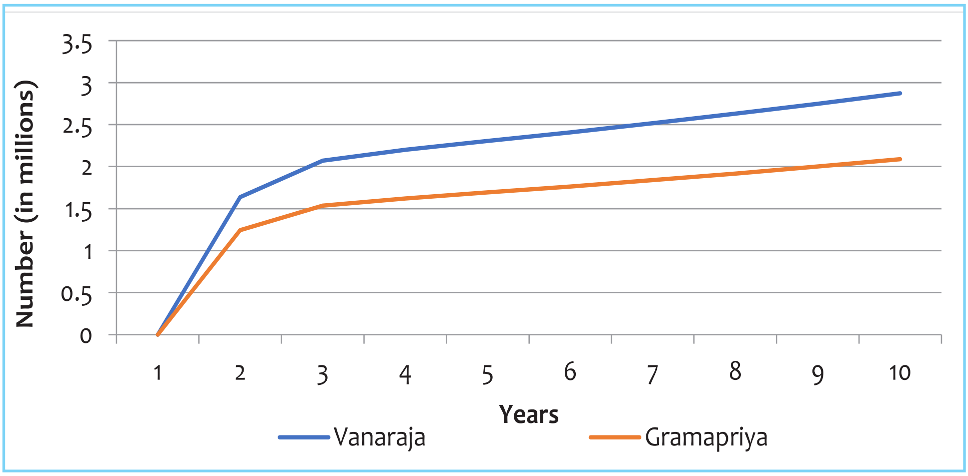
Both Vanaraja and Gramapriya demonstrate superior performance compared to local birds. They produce 3-4 times more eggs and 2-3 times more chicks than local birds, indicating a more rapid increase in flock size and productivity. Their hatching rate is 75% compared to 60% for local birds. Although all varieties have similar productive lifespans, the higher production of eggs and chicks renders Vanaraja and Gramapriya more economically viable for backyard rearing. Vanaraja and Gramapriya reach slaughter age at 3-4 months, significantly earlier than the local varieties (6-12 months), resulting in lower production costs. Male birds of all varieties attain similar market weights, but Vanaraja and Gramapriya achieve this at a younger age, thus offering higher quality meat. Notably, the meat of both varieties commands a comparatively higher price, reflecting consumer preferences for their products.

Table 15. Baseline assumptions for poultry germplasm

Poultry Variety	Total supplied from all sources	% of total backyard improved fowl (chicken)	Parent line (PSP and other agency/ organisations)
Vanaraja	1579158	2.97	25940
Gramapriya	1590463	2.99	16582
Combined	3169621	5.96	42522

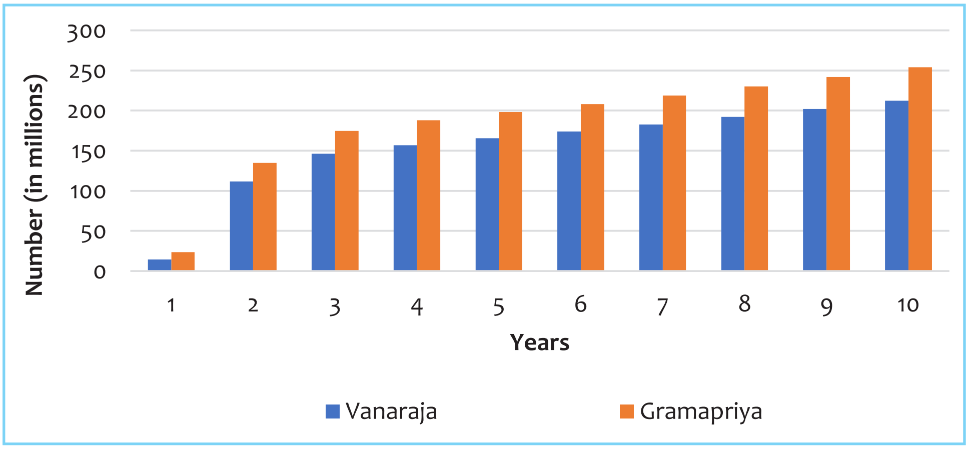
Source: Authors' compilation from expert inputs and institutional records.

Figure 15. Projected number of poultry birds for sale



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 16. Projected number of eggs for sale



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

The reproduction parameters outlined in Table 14 were used to project the populations of Vanaraja, Gramapriya, and indigenous birds over a 10-year period, considering an equal number of day-old chicks, fertile eggs, and mature birds.

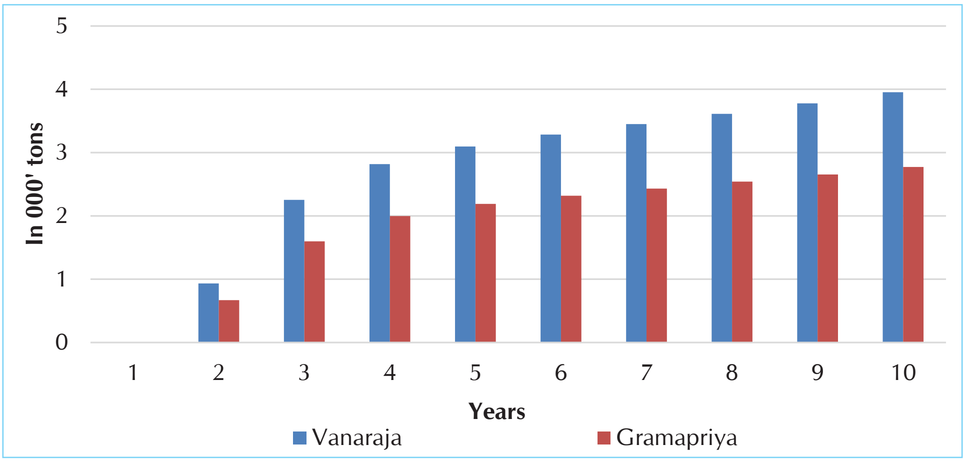
Table 15 further elaborizes on this projection by presenting data related to the dissemination of germplasm in terms of the distribution of breeding stock, eggs, and chicks to farmers.

Figure 15 presents the projected number of total birds ready for sale of Vanaraja and Gramapriya. In the final year, 2.87 million Vanaraja birds and 2.08 million Gramapriya birds are ready for sale.

The projections of egg and meat supplies are presented in Figures 16 and 17, respectively. By the end of 10 years, Vanaraja is expected to have 2.87 million birds ready for sale, whereas Gramapriya is expected to have 2.08 million. The revenue from the sale of Gramapriya eggs is estimated at Rs. 1524.3 million, which is approximately 20% more than that from the sales of Vanaraja eggs (Figure 18).

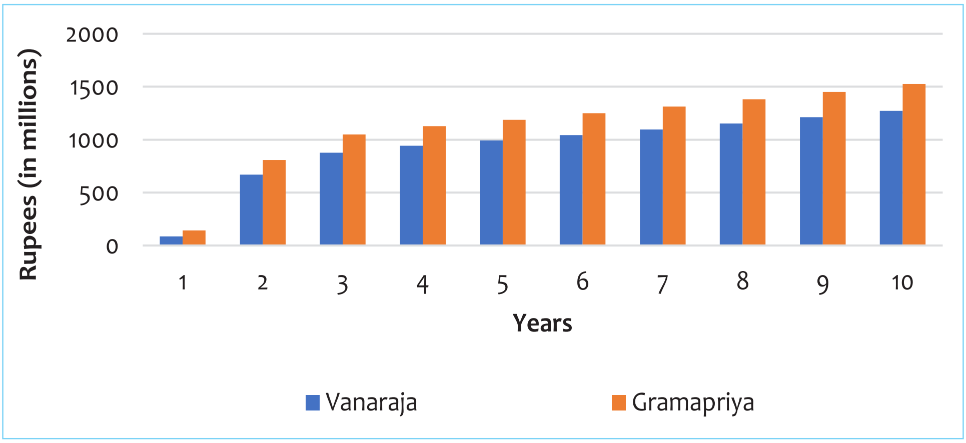
The egg production projections for year 10 show that Gramapriya birds are expected to produce 254.1 million eggs, surpassing Vanaraja's production of 212.2 million. This higher egg production translates into greater revenue for Gramapriya, with estimated sales of Rs 1524.3 million, approximately 20% more than Vanaraja's egg sales. However, when it comes to meat production, Vanaraja takes the lead with an estimated 3953 tons compared to 2772 tons in the case of Gramapriya. This difference in meat production is reflected in the revenue figures, with Vanaraja generating Rs. 1512 million from bird sales, which is 37% more than that of the Gramapriya.

Figure 17. Projected trends in meat supply (in 000' tons)



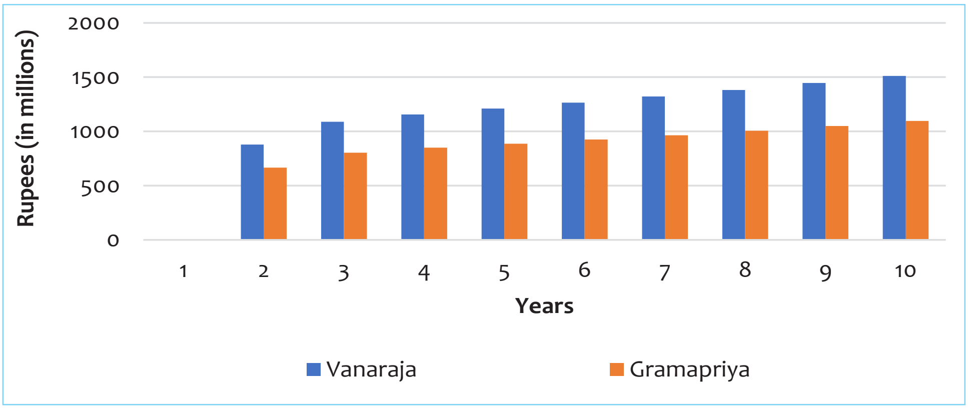
Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 18. Projected trends in revenue from egg sales (in Rs. million)



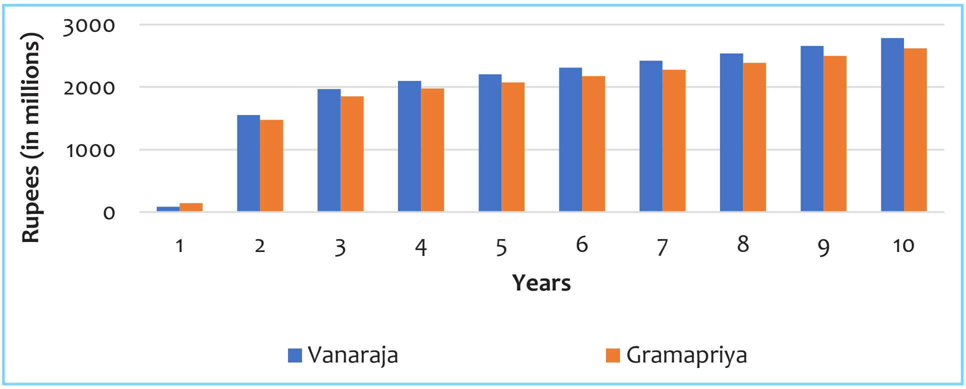
Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 19. Projected trends in revenue from sale of birds (in Rs. million)



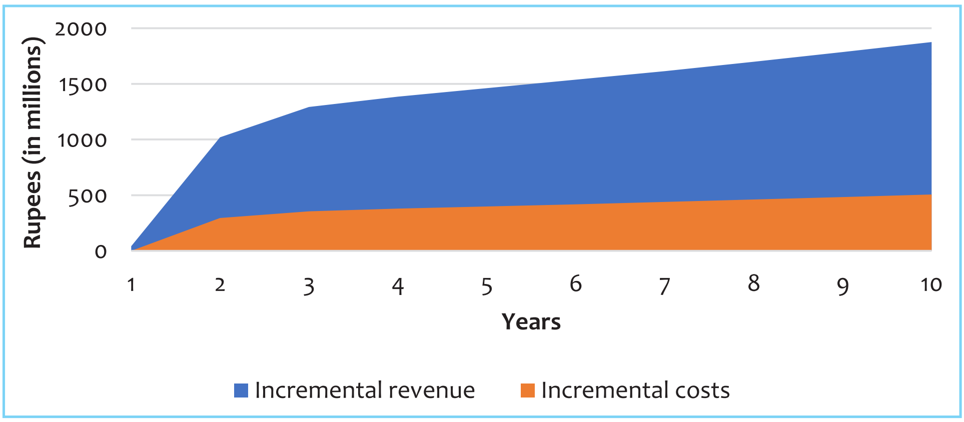
Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 20. Projected trends in total revenue from meat and egg sales (in Rs. million)



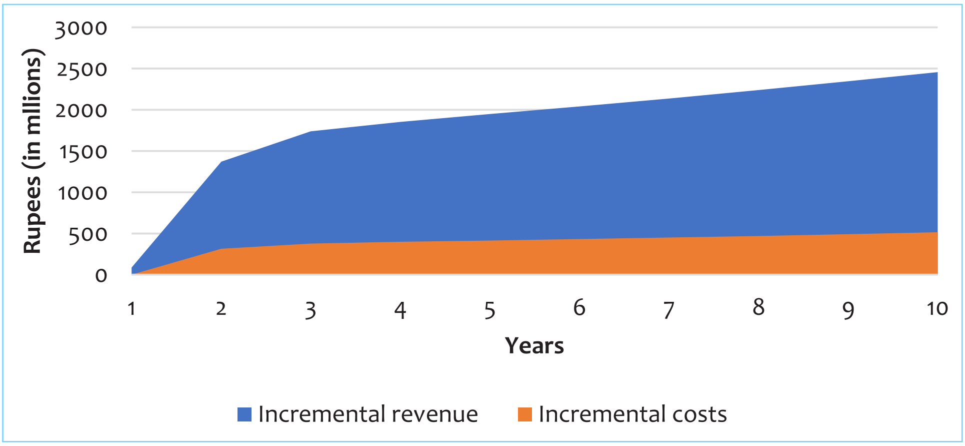
Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 21. Incremental revenues and costs of Vanaraja (in Rs. million)



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

Figure 22. Incremental revenues and costs of Gramapriya (in Rs. million)



Source: Projections by authors using System Dynamics Model based on FGD-informed parameters.

The incremental returns and costs are estimated for Vanaraja (Figure 21) and Gramapriya (Figure 22). The Net Present Value (NPV) of the germplasm of Vanaraja is estimated at Rs. 7858.5 million with a BC ratio of 3.85:1. For Gramapriya, a dual-purpose variety, the Net Present Value (NPV) has been estimated at Rs. 10,598.5 million, and the BC ratio of 4.71:1. Singh et al. (2019) estimated a BC ratio of 4.41:1 for Vanaraja and 1.57:1 for local chickens in the north-eastern hill region of India.

4 Conclusions and Policy Implications

This study conducted a comprehensive economic impact assessment of improved germplasm for various livestock species, including cattle, goats, sheep, pigs, and poultry. The analysis focused on Frieswal cattle, Barbari goats, Avishan sheep, Rani pig, Vanaraja, and Gramapriya chickens. The results show the superior performance and economics of the improved germplasms. For instance, Frieswal cows exhibit significantly higher milk yields than non-Frieswal cows, whereas Barbari goats and Avishan sheep show enhanced prolificacy, growth rates, and body weight. Similarly, the Rani pig breed demonstrated high prolificacy and greater body weight, contributing to improved meat production. This study also highlights the specific advantages of different poultry varieties, with Vanaraja excelling in meat production and Gramapriya in egg production, suggesting that the introduction and widespread adoption of improved germplasms can significantly enhance farmers' livelihoods and contribute to improving human nutrition.

Economically, while improved breeds often require more expenses, their superior production and reproduction traits consistently translate into favorable economic returns in the long run. Among the examples given, Vanraja poultry stands out, with the highest BC ratio of 3.85:1, indicating that for every unit of investment, farmers can expect a return of 3.85 units. Barbari goats follow with a ratio of 2.13:1, while Avishan sheep, Frieswal cows, and Rani pig show ratios of 1.76:1, 1.57:1, and 1.59:1, respectively.

These findings have important implications for investment in animal breeding research and development.

Targeted investment in research: There is a need for sustained investment in research to enhance the genetic potential of all breeds, focusing on traits such as disease resistance and adaptability to diverse agro-climatic conditions. This will ensure the continuous improvement and relevance of these breeds in response to evolving challenges, such as climate change and disease outbreaks.

Extension services: Improve the extension systems to create awareness and impart comprehensive training to farmers, particularly in rural and tribal regions, regarding the advantages and optimal practices for rearing improved breeds. This may encompass the dissemination of knowledge pertaining to optimal feeding strategies, health management protocols, and breeding techniques to maximize the potential of these breeds.

Financial support: The implementation of subsidies, loans, and insurance mechanisms is essential to promote the adoption of these breeds, particularly among small-scale and marginalized farmers. This will facilitate the mitigation of financial barriers associated with the initially higher rearing costs of improved breeds, thereby ensuring broader adoption and equitable access to their benefits.

Infrastructure development: It is necessary to invest in infrastructure, including breeding centers, AIs facilities, hatcheries, feed mills, and veterinary services, to ensure the availability of high-quality inputs and healthcare for these breeds. This investment will facilitate the development of a supportive ecosystem for the sustainable growth of improved livestock and poultry production.

References

Bayan, B., and M. K. Dutta. 2017. Crossbred cattle adoption and its impact on income and household milk consumption among dairy farmers: Empirical evidence from Assam. *Indian Journal of Agricultural Economics* 72(2): 153-165.

Birthal, P. S., and A. K. Jha. 2005. Economic losses due to various constraints in dairy production in India. *The Indian Journal of Animal Sciences 75*(12): 1470-1475.

Birthal, P. S., and D. S. Negi. 2012. Livestock for higher, sustainable and inclusive agricultural growth. *Economic and Political Weekly* 47: 89-99.

Birthal, P. S., V. K. Taneja, and W. Thorpe (Eds.). 2006. Smallholder livestock production in India: Opportunities and challenges. Proceedings of an ICAR–ILRI international workshop held at National Agricultural Science Complex, DPS Marg, Pusa, New Delhi 110 012, India, 31 January - 1 February 2006. NCAP (National Centre for Agricultural Economics and Policy Research) - ICAR (Indian Council of Agricultural Research), New Delhi, India, and ILRI (International Livestock Research Institute), Nairobi, Kenya. pp. 126.

Bystroff, C. 2021. Footprints to singularity: A global population model explains late 20th century slow-down and predicts peak within ten years. *Plos One* 16(5): e0247214. https://doi.org/10.1371/journal.pone.0247214

Dizyee, K., D. Baker, M. Herrero, H. Burrow, L. McMillan, D. N. Sila, and K. M. Rich. 2020. The promotion of amaranth value chains for livelihood enhancement in East Africa: A systems modelling approach. *African Journal of Agricultural and Resource Economics* 15(2): 81-94. https://doi.org/10.22004/ag.econ.307620

GoI. 2019a. 20th Livestock census. Department of Animal Husbandry and Dairying. Ministry of Fisheries, Animal Husbandry and Dairying, Government of India.

GoI. 2019b. *Situation assessment survey of agricultural households and land and livestock holdings of households in rural India*, 2019 (NSS 77th Round)

GoI. 2021. *Productivity of dairy animals*. Ministry of Fisheries, Animal Husbandry & Dairying, Government of India. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1707187.

GoI. 2024a. *Basic Animal Husbandry Statistics*. Department of Animal Husbandry and Dairying, Ministry of Fisheries, Animal Husbandry and Dairying, Government of India.

GoI. 2024b. Report of the Working Group on Crop Husbandry, Agriculture Inputs, Demand and Supply. Government of India, New Delhi.

Hegde, N. G. 2018. Impact of crossbreeding and upgrading of nondescript cattle and buffaloes on livestock quality and income. *Indian Journal of Animal Sciences*88(5): 606-611. https://doi.org/10.56093/ijans.v88i5.80009

Jain, R. N. Nisha, A. Kandpal, and V. R. Nikam. 2025. A deep dive into the impact assessment of agricultural, natural resource management, livestock, and fisheries technologies. Discover Agriculture 3(1):171. https://doi.org/10.1007/s44279-025-00323-3

Jumrani, J., and P. S. Birthal. 2015. Livestock, women, and child nutrition in rural India. *Agricultural Economics Research Review* 28(2): 223-246.

Kapoor, M., S. Ravi, S. Rajan, G. Dhamija, and N. Sareen. 2024. *Changes in India's food consumption and policy implications: A comprehensive analysis of household consumption expenditure survey*. EAC-PM Working Paper Series EAC-PM/WP/30/2024.

Kandpal, A., P. S. Birthal, and S. Mishra. 2024. *From research to impact: Payoffs to investment in agricultural research and extension in India*. Policy Paper 44, ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi.

Lie, H., K. M. Rich, R. van der Hoek, and K. Dizyee. 2018. An empirical evaluation of policy options for inclusive dairy value chain development in Nicaragua: A system dynamics approach. *Agricultural Systems* 164:193-222. https://doi.org/10.1016/j.agsy.2018.03.008

Moritz, M., A. Buffington, A. J. Yoak, I. M. Hamilton, and R. Garabed. 2017. No magic number: An examination of the herd-size threshold in pastoral systems using agent-based modelling. *Human Ecology* 45(4): 525-532.

Mumba, C., E. Skjerve, M. Rich, and K. M. Rich. 2017. Application of system dynamics and participatory spatial group model building in animal health: A case study of East Coast Fever interventions in Lundazi and Monze districts of Zambia. *PLoS One* 12(12): e0189878. https://doi.org/10.1371/journal.pone.0189878

NAAS. 2020. *Livestock improvement through artificial insemination,* Policy Paper 96, National Academy of Agricultural Sciences, New Delhi: pp 20.

Patil, B. R., and H. M. J. Udo. 1997. The impact of crossbred cows at farm level in mixed farming systems in Gujarat, India. *Asian-Australasian Journal of Animal Science*. 10(6):621-628. https://doi.org/10.5713/ajas.1997.621

Prasad, R., A. K. Singh, and L. Singh. 2013. Economic viability of goat breed improvement programme (Barbari × non-descript) at farmer's flock in Uttar Pradesh. *Indian Journal of Animal Sciences* 83(6): 656-660.

Singh, M.K., and M. Gurnani. 2004. Performance evaluation of Karan Fries and Karan Swiss cattle under closed breeding system. 2004. *Asian-Australasian Journal of Animal Sciences* 17(1):1-6.

Singh, M., R. Islam, and R. Avasthe. 2019. Socioeconomic impact of vanaraja backyard poultry farming in Sikkim Himalayas. *International Journal of Livestock Research* 9(3):243-248. https://doi.org/10.5455/ijlr.20181029045005

Sterman, J. D. 2000. *Business dynamics: Systems thinking and modeling for a complex world*. Irwin McGraw Hill. ISBN: 0-07-231135-5.

Sterman, J. D. 2002. *System dynamics: Systems thinking and modeling for a complex world.* *Working Paper Series (ESD-WP-2003-01.13)*, Massachusetts Institute of Technology, Engineering Systems Division. https://dspace.mit.edu/handle/1721.1/102741

Widi, T. S. M., H. Udo, K. Oldenbroek, G. S. Budisatria, E. Baliarti, and A. van der Zijpp. 2020. Designing genetic impact assessment for crossbreeding with exotic beef breeds in mixed farming systems. *Outlook on Agriculture* 50(1):1-12. https://doi.org/10.1177/0030727020915206

Appendices

Appendix 1

Share of exotic/crossbred and indigenous pure/graded animals

Table A1. Share of exotic/crossbred and indigenous pure/graded animals in their total population in India, 2019 (20th Livestock Census)

Livestock	Total (No.)	% of total Population
Cattle		
Total Exotic/Crossbred	51356405	26.55
Indigenous Pure	24935016	12.89
Indigenous Graded	16944891	8.76
Total Indigenous pure/graded	41879907	21.65
Total Non-descript	100230093	51.81
Total Cattle	193460000	100.00
Buffalo		
Indigenous Pure	22353459	20.35
Indigenous Graded	37651387	34.27
Total Indigenous Pure/Graded	60004846	54.62
Total non-descript	49846832	45.68
Total Buffalo	109851678	100.00
Sheep		
Total Exotic/Crossbred	4088133	5.51
Indigenous Pure	19286714	25.99
Indigenous Graded	13293808	17.91
Total Indigenous Pure/Graded	32580522	43.90
Total Non-descript	37552269	50.60
Total Sheep	74220924	100.00
Goat		
Indigenous Pure	40832430	27.43
Indigenous Graded	13490860	9.06
Total Indigenous Pure/Graded	54323290	36.49
Total Non-descript	94561496	63.51
Total	148884786	100.00
Pig		
Total Exotic/Crossbred	1896944	20.95
Total Indigenous Graded	741676	8.19
Total Non-Descript	6416868	70.86
Total	9055488	100.00

Appendix 2

System Dynamic Model Structure

Figure A1. System dynamic model structure for cattle germplasm

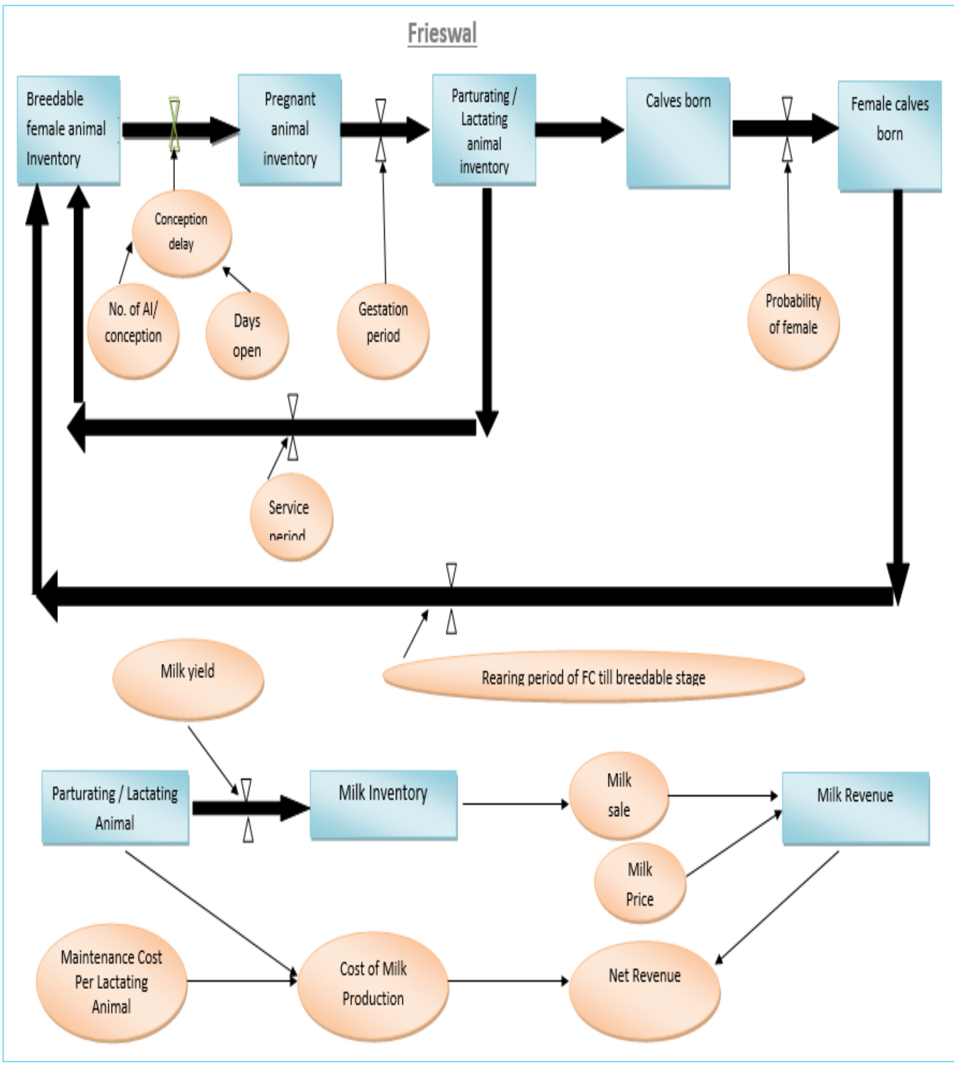


Figure A2. System dynamic model structure for goat and sheep germplasm

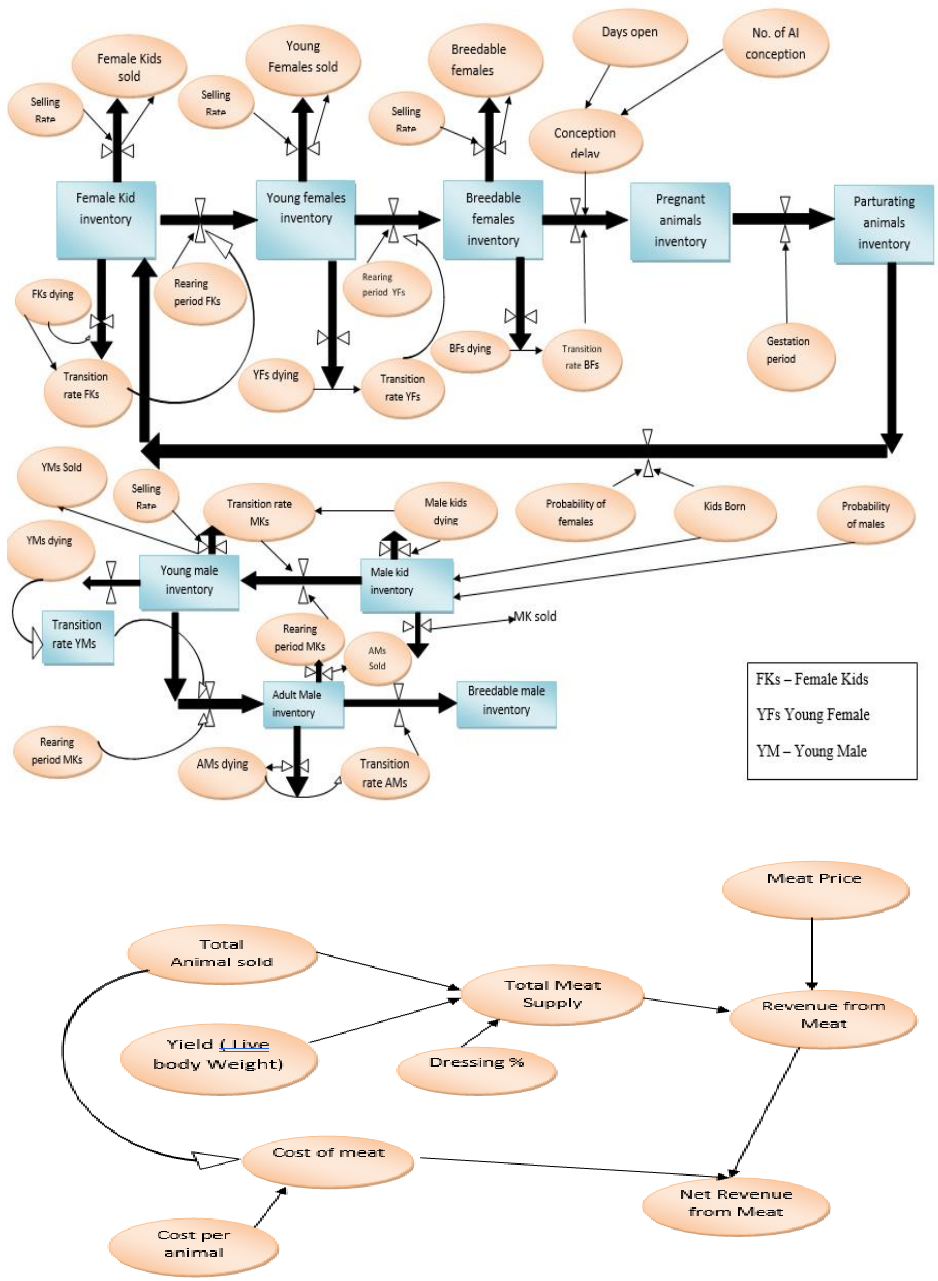


Figure A3. System dynamic model structure for pig germplasm

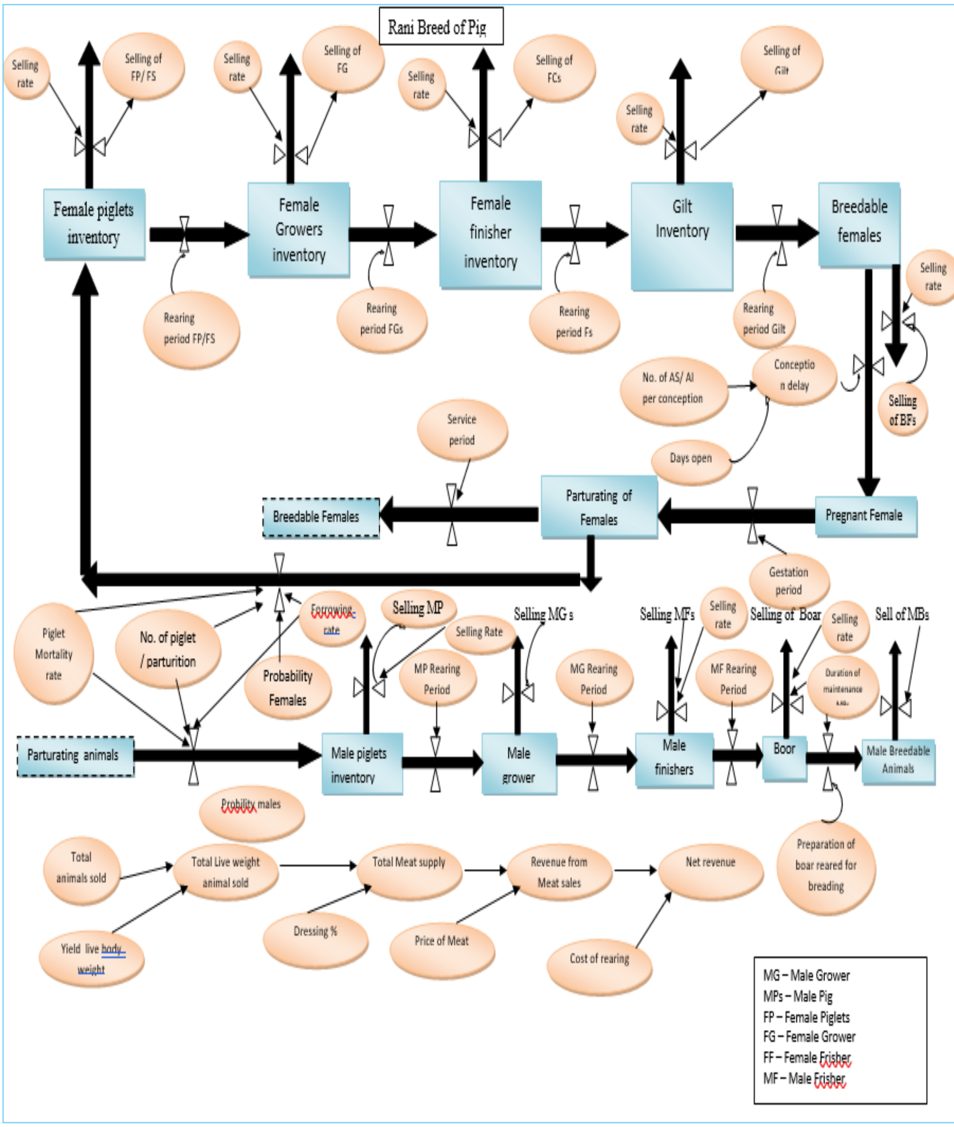
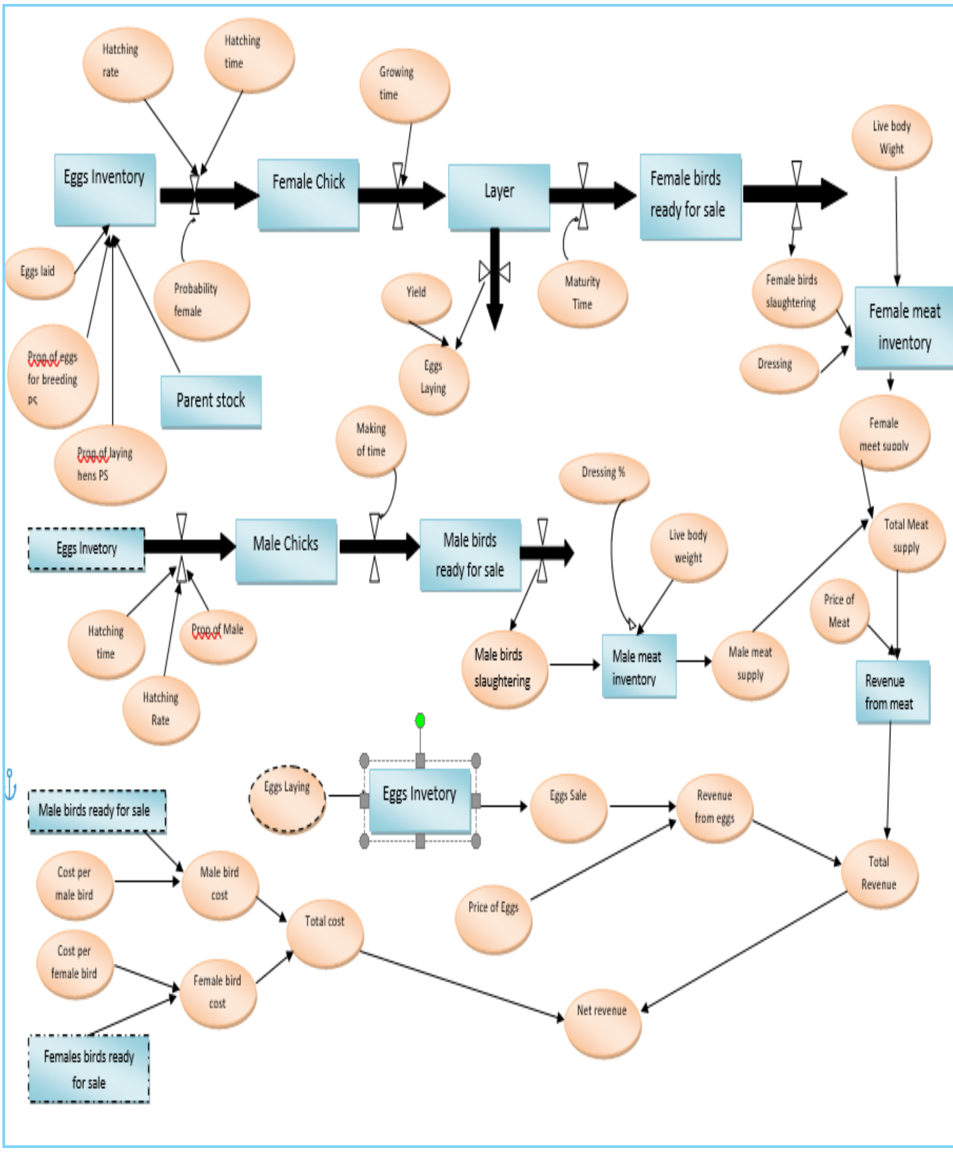


Figure A4. System dynamic model structure for backyard poultry



Model Equations

Table A2. Model equations for Frieswal cattle

total herd size	"3rd_breedable_animal_inventory"+"1st_breedable_animal_inventory"+"1st_pregnant_female_inventory"+"1st_calving_animal_inventory"+"2nd_breedable_animal_inventory"+"2nd_time_pregnant_animal_inventory"+"2nd_calving_animal_inventory"+"3rd_pregnant_animal_inventory"+"3rd_calving_animal_inventory"+"4th_breeding_animal_inventory"+"4th_time_pregnant_animal_inventory"+"4th_time_calving_animal_inventory"+"5th_time_breedable_animal_inventory"+"5th_calving_animal"+"5th_pregnant_animal_inventory"+"6th_time_brredable_animal"+"6th_time_pregnant"+"6th_time_calving_animal"
1st breedable animal dying	"1st_breedable_animal_inventory"*mortality_rate_of_heifer
becoming 1st pregnant animal inventory	"1st_breedable_animal_inventory"*conception_rate/conception_delay_1
conception delay 1	(no_of_AI_required_per_conception-1)*(day_open)
1st pregnant animal dying	"1st_pregnant_female_inventory"*mortality_rate_of_milch_animal
animals ready for 3rd breeding cycle	"3rd_breedable_animal_inventory"*conception_rate/conception_delay_3
3rd pregnant animal dying	"3rd_pregnant_animal_inventory"*mortality_rate_of_milch_animal
becoming 3rd time calving	"3rd_pregnant_animal_inventory"/gestation_period
3rd calving animal dying	"3rd_calving_animal_inventory"*mortality_rate_of_milch_animal
calves being born 3rd lactation	"3rd_calving_animal_inventory"*calving_rate
becoming 4th breeding animal inventory	"3rd_calving_animal_inventory"/service_period
calves being born 3rd lactation	"3rd_calving_animal_inventory"*calving_rate
Female birth 3	surviving_calves_born_3rd_lactation*probability_female
being 4th breedable	Female_calves_3/rearing_period_FC

4th breeding animal dying	"4th_breeding_animal_inventory"*mortality_rate_of_milch_animal
becoming 4th pregnant animal inventory	"4th_breeding_animal_inventory"*conception_rate/conception_delay_4
1st calving animal dying	mortality_rate_of_milch_animal*"1st_calving_animal_inventory"
being 1st calving animals	"1st_pregnant_female_inventory"/gestation_period
calves being born 1st lactation	"1st_calving_animal_inventory"*calving_rate
4th time pregnant animal dying	"4th_time_pregnant_animal_inventory"*mortality_rate_of_milch_animal
being 2nd breedable animal inventory	"1st_calving_animal_inventory"/service_period
female birth 1	surviving_calves_born_1st_lactation*probability_female
becoming 4th calving	"4th_time_pregnant_animal_inventory"/gestation_period
becoming 5th time breedable animal	"4th_time_calving_animal_inventory"/service_period
calves being born 4th lactation	"4th_time_calving_animal_inventory"*calving_rate
being 2nd time pregnant	"2nd_breedable_animal_inventory"*conception_rate/conception_delay_2
Female birth 4	surviving_calves_born_4th_lactation*probability_female
2nd time pregnant animal dying	"2nd_time_pregnant_animal_inventory"*mortality_rate_of_milch_animal
5th pregnant animal dying	"5th_pregnant_animal_inventory"*mortality_rate_of_milch_animal
2nd calving animal dying	"2nd_calving_animal_inventory"*mortality_rate_of_milch_animal
calves being born 2nd lactation	"2nd_calving_animal_inventory"*calving_rate
being 3rd breedable	Female_calves_2/rearing_period_FC
3rd breedable animal dying	"3rd_breedable_animal_inventory"*mortality_rate_of_milch_animal

calves being born 5th lactation	"5th_calving_animal"*calving_rate
being 6th time breedable animals	"5th_calving_animal"/service_period
6th time brredable animal dying	"6th_time_brredable_animal"*mortality_rate_of_milch_animal
6th time pregnant animal dying	"6th_time_pregnant"*mortality_rate_of_milch_animal
6th calving animals dying	"6th_time_calving_animal"*mortality_rate_of_milch_animal
calve being born 6th lactation	"6th_time_calving_animal"*calving_rate
nflowcalvng animal	"1st_calving_animal_inventory"+"2nd_calving_animal_inventory"+"4th_time_calving_animal_inventory"+"3rd_calving_animal_inventory"+"5th_calving_animal"+"6th_time_calving_animal"
total herd size	"3rd_breedable_animal_inventory"+"1st_breedable_animal_inventory"+"1st_pregnant_female_inventory"+"1st_calving_animal_inventory"+"2nd_breedable_animal_inventory"+"2nd_time_pregnant_animal_inventory"+"2nd_calving_animal_inventory"+"3rd_pregnant_animal_inventory"+"3rd_calving_animal_inventory"+"4th_breeding_animal_inventory"+"4th_time_pregnant_animal_inventory"+"4th_time_calving_animal_inventory"+"5th_time_breedable_animal_inventory"+"5th_calving_animal"+"5th_pregnant_animal_inventory"+"6th_time_brredable_animal"+"6th_time_pregnant"+"6th_time_calving_animal"
in-fliow into milk inventory	nflow_calvng_animal*"Milk_yield_non-FPT"
milk sales	milk_inventory

Table A3. Model equations for goat and sheep

female birth	surviving_Kids_born_1st_parturition + surviving_Kids_born_2nd_parturition + surviving_Kids_born_3rd_parturation + surviving_Kids_born_4th_purturition + Kids_being_born_5th_parturation)*probability_of_being_female
selling of female kids	female_kid_inventory*selling_rate_of_female_kids
becoming Young females	((female_kid_inventory*transition_rate_of_female_kids)/rearing_period_of_female_kids_to_young_females)
female kid dying	female_kid_inventory*mortality_rate_of_female_kid
selling of Young females	selling_rate_of_Young_females*Young_females
Young females dying	Young_females*mortality_rate_of_Young_females
becoming Adult females	Young_females*(1-mortality_rate_of_Young_females)/rearing_period_of_Young_females_to_Adult_females
Selling of breedable animal	"1st_time_breedable_females_inventory"*Selling_rate_of_adult_females
Adult breedable female dying	"1st_time_breedable_females_inventory"*Mortality_rate_of_Adult_breedable_females
Becoming Pregnant animals	"1st_time_breedable_females_inventory"*(1-Mortality_rate_of_Adult_breedable_females)*Conception_rate/Conception_delay
becoming parturating	"3rd_pregnant_animal_inventory"*(1-mortality_rate_Adult_females)/gestation_period
Selling of parturating animal	"3rd_parturating_animal_inventory"*Selling_rate_of_adult_females
Kids being born parturation	("3rd_parturating_animal_inventory"*Kidding_rate*Twinning_percentage_other_than_1st_parturition*2) + ("3rd_parturating_animal_inventory"*Kidding_rate*(1-Twinning_percentage_other_than_1st_parturition))
becoming 4th breedable animal inventory	"3rd_parturating_animal_inventory"*(1-mortality_rate_Adult_females)/service_period
Selling of 4th breedable animal	"4th_breedable_animal_inventory"*Selling_rate_of_adult_females
4th breeding animal dying	"4th_breedable_animal_inventory"*mortality_rate_Adult_females

becoming 4th pregnant animal inventory	"4th_breedable_animal_inventory"*(1-mortality_rate_Adult_females)*Conception_rate/Conception_delay
being 1st parturating animals	"1st_Pregnant_animals_inventory"*(1-mortality_rate_Adult_females)/gestation_period
Selling of 1st parturating animal	"1st_parturating_animal_inventory"*Selling_rate_of_adult_females
1st parturating animal dying	mortality_rate_Adult_females*"1st_parturating_animal_inventory"
Kids being born 1st parturition	("1st_parturating_animal_inventory"*Kidding_rate*Twinning_percentage_1st_parturiition*2)+"1st_parturating_animal_inventory"*Kidding_rate*(1-Twinning_percentage_1st_parturiition)*1
4th time pregnant animal dying	"4th_time_pregnant_animal_inventory"*mortality_rate_Adult_females
being 2nd breedable animal inventory	"1st_parturating_animal_inventory"*(1-mortality_rate_Adult_females)/service_period
becoming 4th parturating animal	"4th_time_pregnant_animal_inventory"*(1-mortality_rate_Adult_females)/gestation_period
Selling of 2nd breedable animal	"2nd_breedable_animal_inventory"*Selling_rate_of_adult_females
2nd breedable animal dying	"2nd_breedable_animal_inventory"*mortality_rate_Adult_females
Selling of 4th parturating animal	"4th_time_parturating_animal_inventory"*Selling_rate_of_adult_females
4th time parturating animal dying	"4th_time_parturating_animal_inventory"*mortality_rate_Adult_females
being 2nd time pregnant	("2nd_breedable_animal_inventory"*Conception_rate*(1-mortality_rate_Adult_females))/Conception_delay
becoming 5th time breedable animal	"4th_time_parturating_animal_inventory"*(1-mortality_rate_Adult_females)/service_period
Selling 5th breedable animal	"5th_time_breedable_animal_inventory"*Selling_rate_of_adult_females
becoming 5th time pregnant animal inventory	"5th_time_breedable_animal_inventory"*(1-mortality_rate_Adult_females)*Conception_rate/Conception_delay
2nd time pregnant animal dying	"2nd_time_pregnant_animal_inventory"*mortality_rate_Adult_females

5th pregnant animal dying	"5th_pregnant_animal_inventory"*mortality_rate_Adult_females
becoming 2nd time calving	"2nd_time_pregnant_animal_inventory"*(1-mortality_rate_Adult_females)/gestation_period
becoming 5th calvingl	"5th_pregnant_animal_inventory"*(1-mortality_rate_Adult_females)/gestation_period
Selling of 2nd parturating animal	"2nd_parturating_animal_inventory"*Selling_rate_of_adult_females
Kids being born 2nd parturition	("2nd_parturating_animal_inventory"*Kidding_rate*Twinning_percentage_other_than_1st_parturition*2)+"2nd_parturating_animal_inventory"*Kidding_rate*(1-Twinning_percentage_other_than_1st_parturition)*1
5th time parturating animal dying	mortality_rate_Adult_females*"5th_parturating_animal"
Male birth	(surviving_Kids_born_1st_parturition+surviving_Kids_born_2nd_parturition+surviving_Kids_born_3rd_parturation+surviving_Kids_born_4th_purturition+Kids_being_born_5th_parturation)*probability_of_being_male
selling of male kids	Male_kid_inventory*selling_rate_of_male_kids
Male kid dying	Male_kid_inventory*mortality_rate_of_male_kid
becoming Young males	((Male_kid_inventory*transition_rate_of_male_kids_1)/rearing_period_of_male_kids_to_young_males)
selling of Young males	selling_rate_of_Young_males*Young_males
Young males dying	Young_males*mortality_rate_of_Young_males
becoming Adult males inventory	Young_males*(1-mortality_rate_of_Young_males)/rearing_period_of_Young_males_to_Adult_males
Selling of Adult males	Selling_rate_of_adult_males*Adult_males_inventory
Adult males dying 1	Adult_males_inventory*Mortality_rate_of_Adult_males
Becoming 1st Pregnant animals 1	(Adult_males_inventory*Proportion_of_males_reared_for_breeding*(1-Mortality_rate_of_Adult_males)*(1-Selling_rate_of_adult_males))/Duration_of_maintenance_of_adult_males_for_breeding
Selling of breeding males	Male_breeding_animals_inventory*Selling_rates_of_breedable_males

"Live body wt. female kids"	selling_of_female_kids*Yield_female_kids
selling of female kids	female_kid_inventory*selling_rate_of_female_kids
"Live body wt. Young Females"	selling_of_Young_females*Yield_Young_Females
selling of Young females	selling_rate_of_Young_females*Young_females
"total live body wt."	("Live_body_wt._female_kids"+"Live_body_wt._Young_Females"+"Live_body_wt._Adult_Females"+"Live_body_wt._Male_kids"+"Live_body_wt._Young_Males"+"Live_body_wt._Adult_Males"+"Live_body_wt._Breeding_animals")
"Live body wt. female kids"	selling_of_female_kids*Yield_female_kids
"Live body wt. Male kids"	selling_of_male_kids*Yield_Male_kids
"Live body wt. Young Females"	selling_of_Young_females*Yield_Young_Females
"Live body wt. Young Males"	selling_of_Young_males*Yield_Young_males
"Live body wt. Adult Females"	(Selling_5th_breedable_animal+Selling_5th_parturating_animal+Selling_of_4th_parturating_animal+Selling_of_4th_breedable_animal+Selling_of_1st_breedable_animal+Selling_of_1st_parturating_animal+Selling_of_2nd_breedable_animal+Selling_of_2nd_parturating_animal+Selling_of_3rd_breedable_animal_inventory+Selling_of_3rd_parturating_animal)*Yield_Adult_females
"Live body wt. Adult Males"	Selling_of_Adult_males*Yield_Adult_Males
"Live body wt. Breeding animals"	Selling_of_breeding_males*Yield_Bredding_males
"Live body wt. Male kids"	selling_of_male_kids*Yield_Male_kids
selling of male kids	Male_kid_inventory*selling_rate_of_male_kids
"Live body wt. Young Males"	selling_of_Young_males*Yield_Young_males

selling of Young males	selling_rate_of_Young_males*Young_males
"Live body wt. Adult Females"	(Selling_5th_breedable_animal+Selling_5th_parturating_animal+Selling_of_4th_parturating_animal+Selling_of_4th_breedable_animal+Selling_of_1st_breedable_animal+Selling_of_1st_parturating_animal+Selling_of_2nd_breedable_animal+Selling_of_2nd_parturating_animal+Selling_of_3rd_breedable_animal_inventory+Selling_of_3rd_parturating_animal)*Yield_Adult_females
Selling 5th breedable animal	"5th_time_breedable_animal_inventory"*Selling_rate_of_adult_females
Selling of 4th parturating animal	"4th_time_parturating_animal_inventory"*Selling_rate_of_adult_females
Selling of 4th breedable animal	"4th_breedable_animal_inventory"*Selling_rate_of_adult_females
Selling of 1st breedable animal	"1st_time_breedable_females_inventory"*Selling_rate_of_adult_females
Selling of 1st parturating animal	"1st_parturating_animal_inventory"*Selling_rate_of_adult_females
Selling of 2nd breedable animal	"2nd_breedable_animal_inventory"*Selling_rate_of_adult_females
Selling of 2nd parturating animal	"2nd_parturating_animal_inventory"*Selling_rate_of_adult_females
Selling 5th parturating animal	"5th_parturating_animal"*Selling_rate_of_adult_females
Selling of 3rd breedable animal inventory	"3rd_breedable_animal_inventory"*Selling_rate_of_adult_females
revenue from meat sales	total_meat_supply*Price_of_meat_1
total meat supply	("Live_body_wt._female_kids"+"Live_body_wt._Young_Females"+"Live_body_wt._Adult_Females"+"Live_body_wt._Male_kids"+"Live_body_wt._Young_Males"+"Live_body_wt._Breeding_animals"+"Live_body_wt._Adult_Males")*dressing_percentage
"Live body wt. Adult Males"	Selling_of_Adult_males*Yield_Adult_Males
Selling of Adult males	Selling_rate_of_adult_males*Adult_males_inventory

"Live body wt. Breeding animals"	Selling_of_breeding_males*Yield_Bredding_males
Selling of breeding males	Male_breeding_animals_inventory*Selling_rates_of_breedable_males
total meat supply	("Live_body_wt._female_kids" + "Live_body_wt._Young_Females" + "Live_body_wt._Adult_Females" + "Live_body_wt._Male_kids" + "Live_body_wt._Young_Males" + "Live_body_wt._Breeding_animals" + "Live_body_wt._Adult_Males")*dressing_percentage
"Live body wt. female kids"	selling_of_female_kids*Yield_female_kids
"Live body wt. Male kids"	selling_of_male_kids*Yield_Male_kids
"Live body wt. Young Males"	selling_of_Young_males*Yield_Young_males
"Live body wt. Adult Males"	Selling_of_Adult_males*Yield_Adult_Males
"Live body wt. Breeding animals"	Selling_of_breeding_males*Yield_Bredding_males
"Live body wt. Adult Females"	Selling_5th_breedable_animalSelling_5th_breedable_animalSelling_5th_parturating_animalSelling_of_4th_parturating_animalSelling_of_4th_breedable_animalSelling_of_1st_breedable_animalSelling_of_1st_parturating_animalSelling_of_2nd_breedable_animal
Selling of Adult Females	(Selling_5th_breedable_animal + Selling_5th_parturating_animal + Selling_of_4th_parturating_animal + Selling_of_4th_breedable_animal + Selling_of_1st_breedable_animal + Selling_of_1st_parturating_animal + Selling_of_2nd_breedable_animal + Selling_of_2nd_parturating_animal + Selling_of_3rd_breedable_animal_inventory + Selling_of_3rd_parturating_animal)
Selling of 3rd parturating animal	"3rd_parturating_animal_inventory"*Selling_rate_of_adult_females
Selling 5th parturating animal	"5th_parturating_animal"*Selling_rate_of_adult_females
Selling 5th breedable animal	"5th_time_breedable_animal_inventory"*Selling_rate_of_adult_females
Selling of 4th parturating animal	"4th_time_parturating_animal_inventory"*Selling_rate_of_adult_females

Selling of 4th breedable animal	"4th_breedable_animal_inventory"*Selling_rate_of_adult_females
Selling of 1st breedable animal	"1st_time_breedable_females_inventory"*Selling_rate_of_adult_females
Selling of 1st parturating animal	"1st_parturating_animal_inventory"*Selling_rate_of_adult_females
Selling of 2nd breedable animal	"2nd_breedable_animal_inventory"*Selling_rate_of_adult_females
Selling of 2nd parturating animal	"2nd_parturating_animal_inventory"*Selling_rate_of_adult_females
Selling of 3rd breedable animal inventory	"3rd_breedable_animal_inventory"*Selling_rate_of_adult_females
Adult animals sold	Selling_of_Adult_Females + Selling_of_breeding_males + Selling_of_Adult_males
Selling of Adult males	Selling_rate_of_adult_males*Adult_males_inventory
Selling of breeding males	Male_breeding_animals_inventory*Selling_rates_of_breedable_males
Selling of Adult Females	(Selling_5th_breedable_animal + Selling_5th_parturating_animal + Selling_of_4th_parturating_animal + Selling_of_4th_breedable_animal + Selling_of_1st_breedable_animal + Selling_of_1st_parturating_animal + Selling_of_2nd_breedable_animal + Selling_of_2nd_parturating_animal + Selling_of_3rd_breedable_animal_inventory + Selling_of_3rd_parturating_animal)
Total animals sold	selling_of_male_kids + selling_of_Young_males + Selling_of_Adult_males + Selling_of_breeding_males + Selling_of_Adult_Females + selling_of_Young_females + selling_of_female_kids
selling of male kids	Male_kid_inventory*selling_rate_of_male_kids
selling of Young males	selling_rate_of_Young_males*Young_males
Selling of Adult males	Selling_rate_of_adult_males*Adult_males_inventory
Selling of breeding males	Male_breeding_animals_inventory*Selling_rates_of_breedable_males

Selling of Adult Females	(Selling_5th_breedable_animal + Selling_5th_parturating_animal + Selling_of_4th_parturating_animal + Selling_of_4th_breedable_animal + Selling_of_1st_breedable_animal + Selling_of_1st_parturating_animal + Selling_of_2nd_breedable_animal + Selling_of_2nd_parturating_animal + Selling_of_3rd_breedable_animal_inventory + Selling_of_3rd_parturating_animal)
selling of female kids	female_kid_inventory*selling_rate_of_female_kids
selling of Young females	selling_rate_of_Young_females*Young_females
total cost of meat meat supply	cost_of_meat_per_kg*total_meat_supply
total meat supply	("Live_body_wt._female_kids" + "Live_body_wt._Young_Females" + "Live_body_wt._Adult_Females" + "Live_body_wt._Male_kids" + "Live_body_wt._Young_Males" + "Live_body_wt._Breeding_animals" + "Live_body_wt._Adult_Males")*dressing_percentage
total cost of meat per animal	cost_per_animal*Total_animals_sold
	Total Breedable Animals
Breedable animals	"1st_time_breedable_females_inventory" + "2nd_breedable_animal_inventory" + "3rd_breedable_animal_inventory" + "4th_breedable_animal_inventory" + "5th_time_breedable_animal_inventory"

Table A4. Model equations for pigs

female birth	(surviving_piglets_born_1st_parturition + surviving_piglets_born_2nd_parturation + surviving_piglets_born_3rd_parturation + surviving_piglets_born_4th_parturation)*probability_of_being_female
female piglet dying	"female_piglet/starter_inventory"*"mortality_rate_of_female_piglet/starters"
selling of femalepiglets/starters	"female_piglet/starter_inventory"*"selling_rate_female_piglets/starters"
being starter	"female_piglet/starter_inventory"/rearing_period_starter_to_grower
grower being sold	female_grower*selling_rate_of_female_grower
growers dying	female_grower*mortality_rate_growers
being grower	female_grower/rearing_period_grower_to_finisher
selling of finishers	female_finisher*selling_rate_finishers
finishers dying	female_finisher*mortality_rate_finishers
being finisher	female_finisher/rearing_period_finisher_to_gilt
gilts dying	Gilt*mortality_rate_gilt
selling of gilts	Gilt*selling_rate_gilts
being 1st breedable	Gilt/rearing_period_gilt_to_1st_breedable
1sr breedable dying	"1st_breedable"*Mortality_rate_of_Adult_breedable_females
selling 1st breedable	"1st_breedable"*Selling_rate_of_adult_females
being 1st pregnant	"1st_breedable"*Conception_rate/Conception_delay
1st time pregnant animal dying	"1st_Pregnant_animals_inventory"*mortality_rate_Adult_females
animals ready for3rd breeding cycle	("3rd_breedable_animal_inventory"*Conception_rate)/Conception_delay
3rd time pregnant animal dying	"3rd_pregnant_animal_inventory"*mortality_rate_Adult_females
becoming 3rd time parturating	"3rd_pregnant_animal_inventory"/gestation_period

Selling of 3rdparturating animal	"3rd_parturating_animal_inventory"*Selling_rate_of_adult_females
3rd parturating animal dying	"3rd_parturating_animal_inventory"*mortality_rate_Adult_females
piglets being born3rd parturation	"3rd_parturating_animal_inventory"*Farrowing_rate*"No._of_piglets_born_per_parturation"
becoming 4th breedableanimal inventory	"3rd_parturating_animal_inventory"/service_period
Selling of 4th breedable animal	"4th_breedable_animal_inventory"*Selling_rate_of_adult_females
4th breeding animal dying	"4th_breedable_animal_inventory"*mortality_rate_Adult_females
becoming 4th pregnant animal inventory	"4th_breedable_animal_inventory"*Conception_rate/Conception_delay
being 1st parturating animals	"1st_Pregnant_animals_inventory"*(1-mortality_rate_Adult_females)/gestation_period
Selling of 1st parturating animal	"1st_parturating_animal_inventory"*Selling_rate_of_adult_females
1st parturating animal dying	mortality_rate_Adult_females*"1st_parturating_animal_inventory"
Piglets being born 1st parturition	"1st_parturating_animal_inventory"*Farrowing_rate*"No._of_piglets_born_per_parturation"
4th time pregnant animal dying	"4th_time_pregnant_animal_inventory"*mortality_rate_Adult_females
being 2nd breedable animal inventory	"1st_parturating_animal_inventory"/service_period
becoming 4th parturating animal	"4th_time_pregnant_animal_inventory"/gestation_period
Selling of 2nd breedable animal	"2nd_breedable_animal_inventory"*Selling_rate_of_adult_females
2nd breedable animal dying	"2nd_breedable_animal_inventory"*mortality_rate_Adult_females
Selling of 4th parturating animal	"4th_time_parturating_animal_inventory"*"Selling_rate_of_adult_females_(4th_parturition)"
piglets being born 4th parturation	"4th_time_parturating_animal_inventory"*Farrowing_rate*"No._of_piglets_born_per_parturation"

4th time parturating animal dying	"4th_time_parturating_animal_inventory"*mortality_rate_Adult_females
being 2nd time pregnant	("2nd_breedable_animal_inventory"*Conception_rate)/Conception_delay
2nd time pregnant animal dying	"2nd_time_pregnant_animal_inventory"*mortality_rate_Adult_females
becoming 2nd time calving	"2nd_time_pregnant_animal_inventory"/gestation_period
Selling of 2nd parturating animal	"2nd_parturating_animal_inventory"*Selling_rate_of_adult_females
2nd parturating animal dying	"2nd_parturating_animal_inventory"*mortality_rate_Adult_females
Piglets being born 2nd parturition	"2nd_parturating_animal_inventory"*Farrowing_rate*"No._of_piglets_born_per_parturation"
becoming 3rd breedable animal inventory	"2nd_parturating_animal_inventory"/service_period
Selling of 3rd breedable animal inventory	"3rd_breedable_animal_inventory"*Selling_rate_of_adult_females
3rd breedable animal dying	"3rd_breedable_animal_inventory"*mortality_rate_Adult_females
	Herd Module Male
inflow male piglets	(surviving_piglets_born_1st_parturition + surviving_piglets_born_2nd_parturation + surviving_piglets_born_3rd_parturation + surviving_piglets_born_4th_parturation)*probability_of_being_male
selling of male piglets/starters	"Male_piglet/starter"*"selling_rate_of_male_piglets/starters"
Male piglets/starters dying	"Male_piglet/starter"*"mortality_rate_of_male_piglets/starters"
being male growers	"Male_piglet/starter"/rearing_period_starter_to_grower
male growers selling	male_grower*selling_rate_male_growers
male growers dying	male_grower*mortality_rate_growers
being male finishers	male_grower/rearing_period_grower_to_finisher
male finisher selling	male_finishers*selling_rate_finishers
male finishers dying	male_finishers*mortality_rate_finishers

becoming boars	male_finishers/rearing_period_finisher_to_boar
male boars dying	Boar*Mortality_rate_of_Adult_males
selling boars	Boar*selling_rate_boars
Becoming male breeding animals	(Boar*Proportion_of_males_reared_for_breeding)/ Duration_of_maintenance_of_adult_males_for_ breeding
Selling of breeding males	Male_breeding_animals_inventory*selling_rates_ breeding_males
breeding males dying	Male_breeding_animals_inventory*Mortality_rate_ of_Adult_males
	Meat Output & Revenue
Total LBW female starters	"selling_of_female_piglets/starters"*"Yield_(LBW)_ female_starters"
selling of female piglets/starters	"female_piglet/starter_inventory"*"selling_rate_ female_piglets/starters"
Total LBW Female grower	grower_being_sold+"Yield_(LBW)_growers"
grower being sold	female_grower*selling_rate_of_female_grower
Total LBW female finishers	"Yield_(LBW)_finisher"*selling_of_finishers
selling of finishers	female_finisher*selling_rate_finishers
Total LBW Adult Females	(Selling_of_4th_parturating_animal+Selling_ of_4th_breedable_animal+selling_1st_ breedable+Selling_of_1st_parturating_ animal+Selling_of_2nd_breedable_ animal+Selling_of_2nd_parturating_ animal+Selling_of_3rd_breedable_animal_ inventory+Selling_of_3rd_parturating_ animal)*"Yield_Adult_(LBW)_females"
Selling of 4th parturating animal	"4th_time_parturating_animal_inventory"*"Selling_ rate_of_adult_females_(4th_parturition)"
Selling of 4th breedable animal	"4th_breedable_animal_inventory"*Selling_rate_ of_adult_females
Selling of 1st parturating animal	"1st_parturating_animal_inventory"*Selling_rate_ of_adult_females
Selling of 2nd breedable animal	"2nd_breedable_animal_inventory"*Selling_rate_ of_adult_females
Selling of 2^{nd}parturating animal	"2nd_parturating_animal_inventory"*Selling_rate_ of_adult_females

Selling of 3rd breedable animal inventory	"3rd_breedable_animal_inventory"*Selling_rate_of_adult_females
selling 1st breedable	"1st_breedable"*Selling_rate_of_adult_females
Selling of 3rdparturating animal	"3rd_parturating_animal_inventory"*Selling_rate_of_adult_females
Total LBW Male starter	"selling_of_male_piglets/starters"*"Yield_(LBW)_Male_starters"
selling of malepiglets/starters	"Male_piglet/starter"*"selling_rate_of_male_piglets/starters"
Revenue from meat sales	Total_meat_supply_for_sales*Price_of_meat
Total meat supply for sales	(Total_LBW_Female_grower+Total_LBW_Adult_Females+Total_LBW_Boars+Total_LBW_female_starters+Total_LBW_Breeding_males+Total_LBW_Male_starter+Total_LBW_Male_grower+Total_LBW_male_finishers+Total_LBW_male_finishers+Total_LBW_Female_grower+Total_LBW_female_finishers)*Dressing_%
Total LBW Male grower	male_growers_selling*"Yield_(LBW)_growers"
male growers selling	male_grower*selling_rate_male_growers
Total LBW male finishers	male_finisher_selling*"Yield_(LBW)_finisher"
male finisher selling	male_finishers*selling_rate_finishers
Total LBW Boars	selling_boars*"Yield_(LBW)_Adult_Males"
selling boars	Boar*selling_rate_boars
Total LBW Breeding males	Selling_of_breeding_males*"Yield_(LBW)_Adult_Males"
Selling of breeding males	Male_breeding_animals_inventory*selling_rates_breeding_males
Total meat supply for sales	(Total_LBW_Female_grower+Total_LBW_Adult_Females+Total_LBW_Boars+Total_LBW_female_starters+Total_LBW_Breeding_males+Total_LBW_Male_starter+Total_LBW_Male_grower+Total_LBW_male_finishers+Total_LBW_male_finishers+Total_LBW_Female_grower+Total_LBW_female_finishers)*Dressing_%
Total LBW Breeding males	Selling_of_breeding_males*"Yield_(LBW)_Adult_Males"

Total LBW Boars	selling_selling_boars*"Yield_(LBW)_Adult_Males"boars*"Yield_(LBW)_Adult_Males"
Total LBW male finishers	male_finisher_selling*"Yield_(LBW)_finisher"
Total LBW Male grower	male_growers_selling*"Yield_(LBW)_growers"
Total LBW Male starter	"selling_of_male_piglets/starters"*"Yield_(LBW)_Male_starters"
Total LBW female starters	"selling_of_female_piglets/starters"*"Yield_(LBW)_female_starters"
Total LBW Female grower	grower_being_sold + "Yield_(LBW)_growers"
Total LBW female finishers	"Yield_(LBW)_finisher"*selling_of_finishers
Total LBW Adult Females	(Selling_of_4th_parturating_animal + Selling_of_4th_breedable_animal + selling_1st_breedable + Selling_of_1st_parturating_animal + Selling_of_2nd_breedable_animal + Selling_of_2nd_parturating_animal + Selling_of_3rd_breedable_animal_inventory + Selling_of_3rd_parturating_animal)*"Yield_Adult_(LBW)_females"

Table A5. Model equations for backyard poultry

breeding	IF presence_of_local_value_chains = 0 THEN 0 ELSE (parent_stock*proportion_of_laying_hens*eggs_laid*proportion_of_eggs_for_breeding)
hatching	(Eggs*hatching_rate*proportion_female)/hatching_time
chicks dying	chick_mortality_rate*female_chicks
losses of parent stock	parent_stock*parent_mortality_rate
obtaining parent stock	parent_stock*replacement_rate
growing	female_chicks/growing_time
egg laying	Layers*average_egg_yield_before_reaching_slaughter_stage
layers dying	Layers*layer_mortality_rate
maturing	Layers/maturing_time
adult female birds dying	female_birds_ready_for_sale*layer_mortality_rate
female birds alaughtering	female_birds_ready_for_sale
inflow female meat inventory	female_birds_alaughtering*live_body_weight_female*dressing_percentage
female meat sales	female_meat_inventory
inflow male chicks	(Eggs*hatching_rate*(1-proportion_female))/hatching_time
male birds maturing	male_chicks/male_bird_maturing_time
male chicks dying	male_chicks*chick_mortality_rate
male birds dying	male_birds_ready_for_sale*male_birds_mortality_rate
male birds slaughtering	male_birds_ready_for_sale
inflow male meat inventory	male_birds_slaughtering*live_body_weight_male*dressing_percentage
male meat sales	male_meat_inventory
inflow egg inventory	egg_laying
egg sales	egg_inventory

Policy Papers

Publications

42. Chand, P., T.M. Kiran Kumara, S. Pal, and K. Naik. 2024. *A Spatial Assessment of Sustainability in Indian Agriculture*.
43. Kishore, P., D. Roy, P.S. Birthal and S.K. Srivastava. 2024. *Regulation and Policy Response to Groundwater Preservation in India*.
44. Kandpal, A., P.S. Birthal and S. Mishra. 2024. *From Research to Impact: Payoffs to Investment in Agricultural Research and Extension in India*.
45. Sharma, P., M. Yeasin, R. K. Paul, D.C. Meena and M. E. Anwer. 2024. *Food Price Volatility in India*.
46. Srivastava, S.K., P. Kishore, P.S. Birthal and P.B. Shirsath. 2024. *Harnessing the Potential of Solar-Powered Micro-Irrigation for Sustainable Intensification of Agriculture*.
47. Saxena, R., P. S. Birthal, R. C. Agrawal, P. Sharma, S. J. Balaji, D. K. Pant, and N. Joshi. 2024. *From Local to Global: Opportunities to Accelerate Agriculture Exports from India*.
48. Kishore, P., P. S. Birthal, and S. K. Srivastava. 2025. *The Dilemma of Agricultural Price Policy Reforms: Balancing Food Security, Farmers' Interests, and Sustainability of Natural Resources*.
49. Kumar S., P. S. Birthal, S. Kumar, and R. K. Yadav. 2025. *Economic Impact of Subsurface Drainage Technology: Institutional and Policy Imperatives for Upscaling*.
50. Birthal, P.S., S.K. Srivastava, R. Saxena, S. Godara, P. Chand, P. Kishore, J. Jumrani, A. Kandpal, P. Sharma and D.K. Pant. 2025. *Indian Agriculture to 2047: Reshaping Policies for Sustainable Development*.
51. Balaji, S.J., P.S. Birthal, B.D. Pal, J. Thurlow, E. Gotor, P. Sharma, S.K. Srivastava, I.T. Kingsly, and N. Naresha 2025. *The Future of Food in India: A 2050 Perspective*.
52. Shekhawat, R.S., P. Chand, K.T.M. Kumara, P.C. Moharana, V.S. Rathore, N.R. Panwar, and D. Kumar 2025. *Valuation of Ecosystem Services from Sand Dune Stabilization in Indian Thar Desert*.
53. Choudhary, B.B., P. Sharma, A. K. Roy, V. K. Yadav, S. R. Swami, A. Ghosh, G. Gupta, A. Kandpal, and R. Jain. 2025. *Economic Impact of Forage Varieties*.
54. Bisen, J.P., Kandpal, A., Jain, R., Mondal, B., Kumar, G.A.K, and Nayak, A.K. 2025. *Economic Evaluation of Climate-Resilient Rice Varieties*.
55. Murali, P., Singh, N. P., Jain, R ., Jagadeshwaran, P., and Govindaraj, P. 2025. *India's Sugarcane Revolution: Role of Breeding Innovations*.
56. Shaheen, F. A., K. T. M. Kumara, S. A. Wani, P. Chand, A. Sultan, P. Singh and U. Majeed. 2025. *Competitive and Comparative Advantage of Major Temperate Fruit Crops of India*.

Policy Brief

60. Kumar, N.R. and P.G. Athare. 2025. *Farm Mechanization in India. The Crucial Role of Custom Hiring Services*.
61. Birthal, P.S., S.K. Srivastava and J. Singh. 2025. *From Cereals to High-Value Foods*.
62. Kumar, A. and P. S. Birthal. 2025. *Leveraging Potential of Dung for Energy Security and Sustainable Agriculture*.
63. Srivastava, S.K., P. Kishore, P. S. Birthal, J. Singh and R. R. Sethi. 2025. *Tiered Electricity Pricing for Sustainable Groundwater Use for Irrigation*.
64. Kumar, S., A.K. Sharma, R. Jain, R.K. Yogi, A. Kandpal and P.K. Rai. 2025. *Economic Impact of Improved Mustard Varieties: A Case of Giriraj*.
65. Jain, R., A. Ashok, Nisha and V. Kumar. 2025. *Harvesting Benefits of Drone Technology in Agriculture*.
66. Nikam, V., T.M. Kiran Kumara , S. Godara and P.S. Birthal. 2025. *Enhancing Financial Viability of Farmer Producer Organizations*.
67. Jumrani, J. 2025. *Intra-household double burden of malnutritions in India: Prevalence, Variations and Implications*.
68. Balaji, S.J., M.L. Nithyashree and P.S. Birthal. 2025. *Farm-Nonfarm Linkages in India: Multiplier Effects and Policy Implications*.
69. Chand, K., T.K. Bhattacharya, A. Bhardwaj, Y. Pal, S.C. Mehta and A. Singh. 2025. *From Beast of Burden to Dairy Animal: Transforming Donkey Husbandry for Human Nutrition and Health*.
70. Kumar, B., K.T.M. Kumara, S.L. Jat, and H.S. Jat. 2025. *Economic Impacts of Maize Hybrids*.
71. Sharma, P., D.C. Meena, N.P. Singh, and N. Joshi. 2025. *From Regulation to Liberalization: Impact of Deregulating Horticultural Markets*.
72. Kumar, S., S. K. Sanwal, A. Kandpal, A. Kumar, N. Kulshreshtha, and R. K. Yadav. 2025. *Economic Impact of Salt-tolerant Wheat Varieties*.
73. Singh, N. P., B. Ahuja, S. K. Srivastava, K. V. Rao, S. K. Bal, and N. R. Kumar. 2025. *Climate Resilience of Indian Agriculture across Agro-Climatic Zones*.

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