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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Modeling the transition towards lab-grown milk: future pathways for the Italian dairy-beef system

TESI MAGISTRALE IN FOOD ENGINEERING – INGEGNERIA ALIMENTARE

AUTHOR: ERICA NOSOTTI

ADVISOR: MARGHERITA EMMA PAOLA PERO, ELEONORA CATELLANI

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1. Introduction

Milk has traditionally played a central role in people's diet and continues to represent one of the most widely consumed food products worldwide. However, animal-based food production is raising increasing ethical and environmental concerns, driving growing interest in alternative protein sources. Within this context, several alternatives to dairy products have emerged. Alongside plant-based beverages, which currently represent the most established alternative, recent advances in cellular agriculture have enabled the development of lab-grown milk, an innovative product produced through precision fermentation.

Although still at an early stage of development, lab-grown milk has the potential to significantly transform the dairy industry. In fact, it aims to replicate traditional milk's characteristics while reducing dependence on livestock farming. Several studies have investigated its technological feasibility, environmental performance, and consumer acceptance. However, limited attention has been devoted to understanding its potential impacts on traditional livestock systems. (Hurst & Pant, 2025; Liu et al., 2024)

This aspect is particularly relevant also because dairy farming is deeply interconnected with other sectors. First, it is linked to beef production: through calves, which are sold to fatteners and slaughtered at later stage of growth, and through culled dairy cows, which are slaughtered at the end of their productive life. In addition, dairy herds require feed that can be produced both on-farm and off-farm, which contributes to land occupation. Lastly, animal manure can be converted, through anaerobic digestion, into biogas, which can be further processed to generate electricity, and into digestate, which is mainly used as a fertilizer. This electricity can be used on-farm or fed into the grid. Therefore, changes in milk production may influence herd size, beef production, land occupation, and electricity generation. Consequently, the diffusion of lab-grown milk may generate effects extending far beyond the dairy sector itself. (Mekunye & Makinde, 2024; Rolando et al., 2025; Vinci, 2022)

Therefore, the study was structured around a central overarching research question: *How could the increasing diffusion of lab-grown dairy reshape the* *structure of the traditional Italian dairy sector and its interconnected sectors?*

To achieve this objective, a system dynamics model and a scenario analysis were performed.

2. Methodology

To address the research question, a literature review and a series of interviews were conducted.

First, an extensive literature review was conducted to develop a comprehensive understanding of the Italian dairy sector and its interactions with other interconnected and/or impacted sectors, lab-grown milk, and simulation methods applicable to this case.

Then, semi-structured interviews were conducted with industry experts, including seven dairy farmers, one beef farmer, and one sales agent who is specialized in feed for dairy cattle. The interviews provided practical insights into farm management practices, decision-making processes and the causal relationships linking the dairy sector with the beef, feed, and energy sectors.

The information gathered were used to develop a system dynamics model. First, a Causal Loop Diagram (CLD) was developed to map the main feedback mechanisms and interconnections linking traditional milk, lab-grown milk, and beef production systems. The CLD provided a simplified representation of how changes in demand, prices, and production decisions could propagate across the different sectors. Then, a model, following a stock and flow logic, was constructed on Excel. The objective was to represent the functioning of a traditional dairy farm and to quantify the main dynamics regarding herd management, beef production, feed requirements, and biogas production. The same dynamics were also calculated for beef farms.

Then, a scenario analysis was developed to explore different possible future pathways for the dairy-beef system over the period 2025-2055. Future trajectories for traditional milk, beef, plant-based beverages, and lab-grown milk were derived from market projections available in literature. Based on this, three scenarios were developed, combining trends for dairy products with different trends for beef, in order to assess the potential effects on the system.

The developed scenarios were then presented to two experts in cellular agriculture. The objectives of this validation phase were to assess the plausibility of the made assumptions, to discuss the feasibility of the scenarios, and to gather feedback for their refinement.

After refining them, all scenarios were compared using a set of indicators, including beef production, from both dairy and specialized beef farms, land occupation, and electricity generation.

3. Results

3.1. System Dynamics

3.1.1. Closed Loop Diagram

As regards the CLD, it was structured around three main subsystems: lab-grown milk system, traditional milk system, and meat production system.

Overall, it demonstrates that these three subsystems influence one another through market dynamics and that the adoption of lab-grown milk can lead to structural changes across the entire livestock sector.

In particular, it shows that the potential entry of lab-grown milk into the market could lead to a decline in demand for traditional milk and, consequently, to a reduction in the dairy herd in the long term. Such change could also affect the beef sector, reducing the contribution of meat supply from dairy farms. The response of specialized beef farms would depend, however, on trends in meat demand: if meat demand remains stable, it could lead to an increase in the size of beef herds; conversely, if meat demand also declines, there will be a contraction of this sector as well.

3.1.2. Dairy farm Excel model

As regards the Excel model, it represents the functioning of a hypothetical dairy farm composed of 100 lactating dairy cows and quantifies the main biological and productive processes occurring within the system.

Starting from the dairy herd, the model estimates variables such as milk production, calf generation, meat production from culled cows, feed requirements, and manure production.

By linking these variables, the model captures how changes in traditional milk production affect herd size and generate cascading effects on meat production, land occupation, and electricity generation.

3.1.3. Specialized beef farm Excel model

The same modelling approach was subsequently applied to a reference specialized beef farm.

To estimate the size of the beef sector, interview findings were combined with literature data. In particular, experts indicated that approximately 40% of total beef production originates from dairy farms, while the remaining share is supplied by specialized beef farms. Based on this assumption, the initial level of meat production from beef herds was estimated and incorporated into the model.

The model was then used to quantify the contribution of specialized beef farms to total meat production, as well as the associated feed requirements, land occupation, and electricity generation.

3.2. Scenario Analysis

To explore the potential implications of lab-grown milk adoption, three alternative scenarios were simulated over the period 2025-2040.

The differentiation among scenarios reflects the uncertainty surrounding the relationship between dairy and beef production during protein transition. While the diffusion of dairy alternatives is expected to reduce demand for traditional milk, the future response of the beef sector remains unclear.

For this reason, three possible pathways were considered: a simultaneous decline in both milk and meat production, a transition affecting only the dairy sector while total meat production remains constant, and an intermediate pathway in which meat production follows the decline in milk with a delayed response.

The percentages are shown in *Table 1* and *Table 2*.

Table 1 Dairy sector production shares forecast

	2025	2035	2045	2055
Traditional milk	90%	79%	67%	55%
Plant-based beverages	10%	20%	28%	35%
Lab-grown milk	-	1%	5%	10%

Table 2 Traditional meat production forecast

	2025	2035	2045	2055
Scenario 1	-	-12%	-26%	-39%
Scenario 2	-	-	-	-
Scenario 3	-	-	-12%	-26%

The developed scenarios were implemented in the Excel models to evaluate their effects on the main variables characterizing the dairy-beef system. Particular attention was given to total meat production, land occupation, and electricity generation, as these indicators capture the most significant impacts associated with the diffusion of lab-grown milk.

3.2.1. Total meat production

The evolution of total meat production, shown in *Figure 1*, significantly differs across the three scenarios.

In Scenario 1, meat production progressively declines in both dairy and beef sectors over time. Scenario 2 maintains the highest production levels throughout the simulated period, as specialized beef farms compensate for the reduction in meat originating from dairy farms.

Scenario 3 initially follows a trajectory similar to Scenario 2, but gradually shifts towards lower production levels as the delayed transition of the beef sector takes effect.

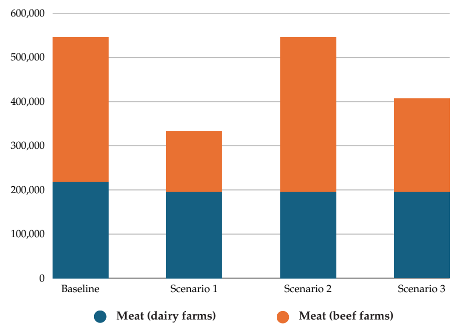

Figure 3 Comparison of scenarios – meat production

3.2.2. Electricity generation

Electricity generation, as it can be seen in *Figure 2*, decreases in all scenarios over the analyzed period. Since electricity is produced from livestock manure, a reduction in herds size results in a lower availability of feedstock for energy production.

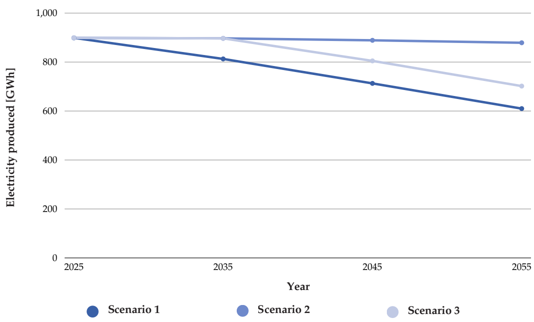

Figure 2 Comparison of scenarios – electricity generation

Scenario 2 produces the highest amount of electricity because the expansion of specialized beef farms partially offsets the reduction in dairy herds, allowing electricity production to remain high. Conversely, Scenarios 1 and 3 show a more significant decline over time due to a more pronounced contraction of livestock activities.

3.2.3. Land occupation

Land occupation, as shown in *Figure 3*, follows a similar path compared to that observed for electricity generation.

Scenario 1 shows the largest reduction in land occupation, reflecting the simultaneous decline of both dairy and beef herds and the consequent reduction in feed requirements.

In contrast, Scenario 2 maintains higher land occupation levels throughout the simulation period, as the expansion of specialized beef farming offsets the reduction in land required by the dairy sector.

Scenario 3 occupies an intermediate position, although its long-term trajectory gradually converges towards Scenario 1.

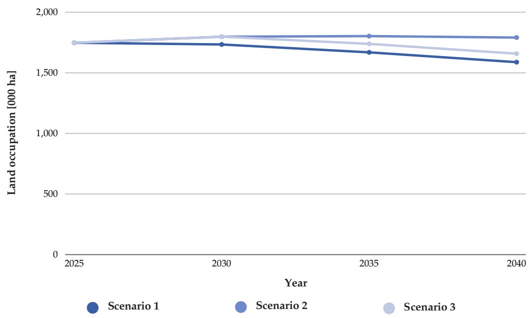

Figure 1 Comparison of scenarios – land occupation

4. Discussion

The results show that a reduction in traditional milk production can generate effects that extend beyond the dairy sector. Indeed, a decline in the number of dairy cows affects the availability of meat from dairy farms and leads to changes in land occupation and energy consumption.

A relevant aspect that emerged from the scenario analysis concerns the relationship between the dairy and beef sectors. In fact, the analysis shows that different future trends in meat consumption can amplify or mitigate the effects generated by the decline in traditional milk production. Consequently, the future evolution of the beef sector is expected to be a key factor in determining the overall impact of the protein transition on livestock-related activities.

The analysis also highlights the existence of environmental trade-offs. On one hand, if the number of animals decreases, the demand for feed and land occupation decreases, potentially reducing pressure on agricultural resources. On the other hand, fewer animals mean less manure and, consequently, less electricity that can be generated from biogas plants and inserted to the grid. Therefore, although the widespread adoption of lab-grown milk could reduce some of the environmental impacts associated with livestock farming, such as land occupation, it could also reduce the contribution of farms to renewable energy production. This effect could be further amplified by the fact that the production process for lab-grown milk is highly energy-intensive, which could lead to an increase in overall electricity demand throughout the supply chain.

5. Conclusions

The aim of this thesis was to analyze, using a systems dynamics approach and a scenario analysis, how the spread of lab-grown milk could affect the Italian dairy sector and related sectors. The results suggest that the adoption of alternatives to dairy products could lead to significant changes in livestock-related activities, with the future evolution of the beef sector emerging as a key factor in determining the extent of these impacts.

The developed model highlights the importance of considering multiple transition pathways when assessing the consequences of alternative proteins, as different assumptions lead to substantially different results. At the same time, the results reveal potential trade-offs associated with the protein transition, particularly between reducing the use of agricultural resources and decreasing renewable energy production on-farms.

Overall, this research demonstrates the importance of adopting a systemic perspective when analyzing emerging food technologies, highlighting the need to consider interactions between interconnected systems. Future research could expand on this model by incorporating additional economic and environmental dimensions, such as GHG emissions or water consumption, as well as the energy requirements associated with the production of lab-grown milk.

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