

Linking Environmental Impacts and Nutritional Value in a Life Cycle Perspective for Different Dairy Products

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Abstract – The dairy sector faces increasing pressure to reduce environmental impacts while maintaining nutritional quality and product diversity. Cheese production is particularly complex, as it involves a wide range of processing technologies and energy demands, from fresh cheeses to long-ripened products. This study presents an evaluation based on Environmental Product Declarations and Life Cycle Assessment applied to fourteen dairy and plant-based products, including milk, fresh products, cheese, and plant-based alternatives. Environmental impacts are expressed as Global Warming Potential (GWP, kg CO₂eq/kg product) and disaggregated across upstream, core, and downstream phases. For studies with limited system boundaries, downstream proxy values, covering distribution, household refrigeration, and packaging end-of-life, were estimated using a harmonized set of assumptions to ensure cross-product comparability. To move beyond mass-based functional units, impacts are also expressed relative to a Nutrient Density Unit (NDU) encompassing energy, protein, fat, carbohydrates, and calcium, key nutrients in which dairy products excel. Further analyses examine the influence of post-farm processing efficiency through five decarbonization scenarios, including energy efficiency improvements and industrial heat pump electrification under varying electricity mixes, applied to four representative products and address the robustness of the nutritional metric through a simplified Nutrient Rich Food index in which fat is treated as a nutrient to limit. Results show that while mass-based GWP favours minimally processed and plant-based products (0.72–1.6 kg CO₂eq/kg) over long-ripened cheeses (9–20 kg CO₂eq/kg), nutritional normalization substantially narrows, and in some cases reverses, this gap: mean GWP/NDU values are 39 for milk, 34 for fresh dairy, 30 for cheese, and 12 for plant-based alternatives, reducing the category-level difference from approximately thirteen-fold to roughly two-and-a-half-fold. Processing decarbonization reduces GWP/NDU by 4–24 % depending on product type, with UHT milk showing the strongest response and long-ripened cheeses the most limited, given the dominance of upstream agricultural emissions. The NRF-based robustness check confirms that relative product rankings remain broadly stable under alternative nutritional metrics. This

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framework supports transparent sustainability communication, product benchmarking, and evidence-based decision-making in the food sector.

Keywords – Cheese production; energy consumption; Environmental Product Declaration (EPD); Life Cycle Assessment (LCA); Nutritional Life Cycle Assessment (nLCA).

1. INTRODUCTION

The food sector is one of the largest contributors to global greenhouse gas (GHG) emissions, responsible for an estimated 33 % of total anthropogenic emissions, with animal-derived products, and dairy in particular, representing a disproportionate share of this burden [1], [2]. Dairy production spans a wide spectrum of processing intensities, from minimally processed fluid milk to long-ripened hard cheeses, each associated with markedly different environmental profiles [3]. At the same time, growing consumer awareness and tightening EU policy frameworks, including the Farm to Fork Strategy and the Green Deal, are placing increasing pressure on the food sector to demonstrate, quantify, and reduce its environmental footprint [4].

Life Cycle Assessment (LCA) and Environmental Product Declarations (EPDs), grounded in ISO 14040/14044 standards, provide the most rigorous and internationally recognized tools for this quantification [5]. EPDs offer certified, third party verified primary data at the product level, making them a valuable complement to peer-reviewed LCA studies. However, a persistent challenge in dairy sustainability assessment is the comparability of results across independently produced LCA studies and EPDs: differences in system boundaries, allocation methods, background databases, co-product handling, and electricity grid assumptions can lead to substantial variation in reported impacts even for the same product category [6], [7]. Reviews of cheese LCA studies consistently highlight the sensitivity of GWP results to methodological choices, particularly allocation, with reported values for the same product varying by up to 60 % depending on the method applied [8].

A further and increasingly discussed limitation of conventional LCA is the use of product mass as the sole functional unit. Comparing the environmental performance of foods per kilogram of product implicitly assumes nutritional equivalence, which is manifestly inappropriate when contrasting products as nutritionally different as liquid milk, fresh mozzarella, aged hard cheese, or plant-based beverages [9], [10]. This concern has given rise to the field of nutritional LCA (nLCA), which integrates nutritional value into the functional unit so that environmental impacts are expressed per unit of nutritional contribution delivered to the consumer [11].

Beyond the question of environmental metrics, dairy processing is also notable for its energy intensity [12], [13]. Across the full supply chain, manufacturing and distribution operations require substantial thermal and electrical energy inputs for pasteurization, sterilization, fermentation, and refrigeration at multiple stages, from raw milk cooling to cheese maturation and cold chain distribution [14]. While upstream agricultural emissions dominate the life cycle GWP of most dairy products, post-farm processing represents the stage most directly under the control of industrial operators and most amenable to targeted engineering intervention. Energy audits conducted across traditional cheese manufacturing facilities have consistently identified specific electricity consumption in the range of 0.15–0.28 kWh per litre of processed raw milk, with benchmarking analyses suggesting that convergence toward average performance levels could deliver electricity savings on the order of 19–21 % [15]. For thermally intensive products such as UHT milk and long-ripened

cheeses, thermal energy demand for process heat represents a further major decarbonization lever [16]. Among available solutions, industrial heat pumps are particularly relevant to the dairy sector because they enable the replacement of fossil-based process heat with electricity, while simultaneously recovering and upgrading low-temperature waste heat streams, such as condenser heat from refrigeration systems or process wastewater to useful thermal levels [13].

Despite this growing body of work, several methodological gaps limit the scope and comparability of existing nLCA studies. Most analyses draw on a single data source or product category, and the downstream life-cycle phases, distribution, household refrigeration, packaging end-of-life, are frequently missing or heterogeneously defined across studies, making system-boundary-consistent cross-product comparisons difficult without explicit harmonization assumptions. Furthermore, while post-farm processing decarbonization is increasingly recognized as a relevant engineering lever, its interaction with nutritionally normalized environmental performance has received limited systematic attention: whether the GWP improvements achievable through energy efficiency measures and heat pump electrification are sufficient to meaningfully shift the relative positioning of dairy products, when measured per unit of nutritional value rather than per mass, remains an open question with direct relevance for investment prioritization and sustainability communication.

This paper addresses these gaps through three specific contributions: the construction of a harmonized cradle-to-grave dataset covering fourteen dairy and plant-based products, with transparent downstream proxy assumptions to ensure system-boundary consistency; the application and robustness testing of a Nutrient Density Unit (NDU) functional unit encompassing energy, protein, fat, carbohydrates, and calcium, and finally the quantitative assessment of realistic post-farm processing decarbonization scenarios, including energy efficiency improvements and industrial heat pump electrification under varying electricity mixes, on nutritionally normalized GWP. Together, these elements provide a methodologically transparent and practically oriented framework for comparing the environmental performance of dairy and plant-based products in a manner that accounts for both nutritional value and processing innovation potential.

The paper is structured as follows: Section 2 presents the data sources, system boundary harmonization procedure, nutritional characterization, and scenario definitions. Section 3 reports the results of the mass-based and NDU-normalized comparisons, the processing efficiency scenarios, and the NDU robustness check. Section 4 draws conclusions from the analysis, discusses the implications of the adopted functional unit and the processing decarbonization scenarios, and identifies key avenues for future research.

2. MATERIALS AND METHODS

2.1. Data Sources

This study evaluates the environmental performance of a range of dairy products and plant-based alternatives by integrating data from EPDs and peer-reviewed LCA studies. The dataset was constructed to represent different levels of processing within the dairy sector, from minimally processed products such as milk to long-ripened cheeses, and to include plant-based alternatives commonly considered substitutes for dairy products. The analysed products were grouped into four categories: milk products, fresh dairy products, cheeses, and plant-based products. Milk products include UHT milk, ESL semi-skimmed milk and fresh semi-skimmed milk. Fresh dairy products comprehend mozzarella, ricotta, and stracchino. Cheeses include Grana Padano PDO (9 and 12 months), Asiago, Toma di Lanzo, and Cheddar. Plant-based alternatives include soy and oat milk, and tofu.

Primary environmental data were obtained from EPDs available in the EPD International Database, with specific documents from Granarolo (ESL milk, mozzarella, ricotta, and stracchino), Mukki (fresh milk), and OraSi (soy milk). For products not covered by EPD documentation, environmental data were obtained from peer-reviewed LCA studies addressing ripened cheeses and plant-based alternatives. For each source, the study extracted the reported GWP results, the available life-cycle phase disaggregation, and the declared system boundaries. The Table A in Annex summarises the analysed products, data sources, background databases, study type, and original system boundaries.

All sources were accessed for their life cycle inventory data, GWP characterisation results, and declared system boundaries.

A key methodological premise of this work is that EPDs and literature-based LCAs are inherently non-harmonised documents. They are produced by different organisations, under different Product Category Rules, using different background databases, allocation procedures, electricity mixes, and spatial and temporal scopes. This methodological plurality is not a flaw of the individual studies, but it limits the precision of direct inter-product comparison. For this reason, the results presented in this paper are interpreted primarily as directional indicators and category-level patterns rather than as definitive product rankings.

2.2. System Boundaries and Downstream Proxy Estimation

The environmental indicator adopted in this study is Global Warming Potential (GWP) expressed as kilograms of CO₂ equivalent per kilogram of product (kg CO₂eq/kg). For each product, the total impact was decomposed into three life-cycle phases: upstream, core processing, and downstream.

The upstream phase includes agricultural production of milk and other primary inputs, as well as packaging production and transport of materials to the processing facility. The core phase corresponds to industrial processing within the dairy plant, including electricity consumption, thermal energy use, refrigeration, and water use associated with manufacturing operations. The downstream phase includes product distribution, household refrigeration during storage, packaging end-of-life management, and food waste.

A major challenge in comparing environmental results across EPDs and literature-based LCA studies is the heterogeneity of system boundaries. While several EPDs report impacts from cradle-to-grave, some literature studies provide results only up to the factory gate or exclude specific downstream components. In the dataset analysed in this study, downstream stages were partially or entirely missing for several products, including UHT milk, Grana Padano PDO (9 and 12 months), Toma di Lanzo, oat milk, and Tofu.

To improve comparability across products, missing downstream contributions were reconstructed through transparent proxy assumptions. These estimates were not intended to reproduce the exact logistics, storage conditions, or waste management of each specific product. Rather, they were developed to provide a consistent methodological approximation for cross-product comparison under a harmonised downstream scope [23].

The downstream phase was decomposed into three main components: distribution, household refrigeration during storage, and packaging end-of-life (including potential waste) [24]. For each of these components, a set of standardized estimation rule was applied.

All assumptions adopted for the proxy estimation are summarized in Table 1. The resulting downstream values should therefore be interpreted as order-of-magnitude harmonisation estimates, suitable for comparative analysis, rather than as exact product-specific measurements.

TABLE 1. ASSUMPTION USED FOR DOWNSTREAM PROXY ESTIMATION

Downstream component	Methodological assumption	Parameter used
Distribution	Impact normalized using loading unit transport capacity	Product mass per loading unit
Household refrigeration	Impact scaled according to occupied refrigerator volume and storage duration	Product volume, storage time (½ shelf life)
Packaging end-of-life	Reference packaging system selected from EPDs with similar materials and mass	Packaging material and weight

2.3. Nutritional Characterization and Nutrient Density Unit

Environmental comparison between food products based solely on mass may lead to misleading conclusions because foods differ substantially in their nutritional role with human diets. To address this limitation, environmental impacts were also normalized using a nutrient density indicator, following the principles of nutritional LCA (nLCA), which links environmental performance to the nutritional value delivered by foods [25].

Nutritional values per 100 g of product were collected from EPD documentation, product labels, and nutritional databases. Five nutrients were considered: energy, protein, fat, carbohydrates, and calcium. These nutrients were selected to reflect the nutritional role of dairy products, which are widely recognised as nutrient-dense foods and important dietary sources of high-quality protein and bioavailable calcium. In particular, dairy products are important dietary sources of high-quality protein and highly bioavailable calcium, as well as contributing to daily energy intake and macronutrients supply [26].

For each nutrient i , a nutrient ratio q_i as:

$$q_i = \frac{N_i}{RI_i} \quad (1)$$

where N_i is the nutrient content of the product and RI_i is the corresponding reference intake.

The Nutrient Density Unit (NDU) was then defined as the arithmetic mean of the five nutrient ratios:

$$NDU = \frac{1}{5} \sum_{i=1}^5 q_i \quad (2)$$

Reference intake values were taken from EU Regulation 1169/2011, using 2000 kcal for energy, 50 g for protein, 70 g for fat, 260 g for carbohydrates, and 800 mg for calcium [27].

The objective of the NDU is not to construct a dietary quality, or healthfulness index, but to compare the environmental efficiency with which foods deliver selected nutritionally relevant components. The NDU is therefore conceived as a functional unit that consider the nutritional value that is delivered rather than as an assessment of whether the intake of each nutrient should be encouraged or limited from a dietary perspective. For this reason, all five nutrients were treated as positive contributors within the main NDU formulation. In particular, total fat was retained because it contributes materially to the macronutrient profile, energy density, and overall nutritional composition of dairy products. This choice does not imply that higher fat intake is always desirable from a health perspective; rather, it reflects the role of fat as part of the nutritional content delivered by the product. Nutritional values and the corresponding NDU values for all analysed products are reported in Table B in Annex.

Environmental impacts were therefore expressed using two complementary metrics: the conventional GWP per kg of product and the GWP per NDU, the latter representing the environmental intensity per unit of delivered nutritional value.

2.4. Additional Analyses

Beyond the core comparison, an additional scenario analysis was conducted to examine the potential effect of post-farm technological improvements on nutritionally normalised environmental performance.

Although upstream agricultural emissions dominate the total GWP of dairy products, post-farm stages are the part of the system most directly influenced by industrial and engineering decisions. This includes plant utilities, thermal integration, refrigeration, storage, logistics, and waste management. Within this broader post-farm domain, the processing stage was selected as the most suitable entry point for quantitative analysis because it is both energy intensive and directly shaped by plant configuration and operating choices.

Based on the literature on dairy processing efficiency and electrification, five processing configurations were considered for four representative products: ESL semi-skimmed milk, UHT milk, mozzarella, and Grana Padano PDO 12 months. The configurations were: current conditions, efficiency improvement only, heat pump electrification under the current electricity mix, heat pump electrification with 50 % renewable electricity, and heat pump electrification with near-zero-emission electricity.

The scenario assumptions were based on: i) electricity-saving potentials of about 20 % reported in dairy processing plants; ii) replacement of fossil-based process heat with an industrial heat pump operating at COP = 4; and iii) progressive decarbonization of electricity supply. In all scenarios, the nutritional denominator was kept constant and only the processing-related GWP contribution was modified. The purpose of this analysis is not to provide predictive plant-specific decarbonization estimates, but to assess the extent to which technically plausible processing improvements may influence total GWP/NDU.

A second additional analysis was conducted to test the robustness of the results with respect to the choice of nutritional functional unit. For this purpose, environmental impacts were recalculated using a simplified Nutrient Rich Food type indicator. This additional analysis was also intended to explicitly address the sensitivity of the results to the treatment of total fat in the main NDU formulation.

The full NRF 9.3 formulation could not be applied because the complete nutritional dataset required for all products was not consistently available across the analysed sources. A simplified NRF indicator was therefore constructed using the nutritional variables available in the dataset [28]. Protein and calcium were included as nutrients to encourage, while total fat was included as a nutrient to limit. The simplified index was calculated as:

$$NRF_{\text{simplified}} = \frac{N_{\text{protein}}}{RI_{\text{protein}}} + \frac{N_{\text{calcium}}}{RI_{\text{calcium}}} - \frac{N_{\text{fat}}}{RI_{\text{fat}}} \quad (3)$$

Environmental impacts were then expressed as GWP per unit of $NRF_{\text{simplified}}$. This robustness check allows verification of whether the relative positioning of products remains stable when the nutritional metric explicitly includes a limiting nutrient.

Since calcium is one of the terms included in the simplified NRF formulation, products lacking reliable calcium information could not be included in this analysis. Toma di Lanzo was therefore excluded from the NRF-based comparison due to the absence of a reliable calcium value in the available nutritional dataset.

Fig. 1 summarizes the overall methodological workflow, from source selection and boundary harmonization to nutritional normalization and additional analysis.



Fig. 1. Methodological framework.

3. RESULTS

3.1. GWP per kg of Product

Fig. 2 presents the total GWP (kg CO₂eq/kg product) for all products, disaggregated by upstream, core, and downstream phases. The downstream contribution is highlighted with a distinct colour (light blue) to indicate the portions that were not reported in the original studies and were therefore estimated using the proxy assumptions described in the methods section in order to ensure a consistent system boundary across products.

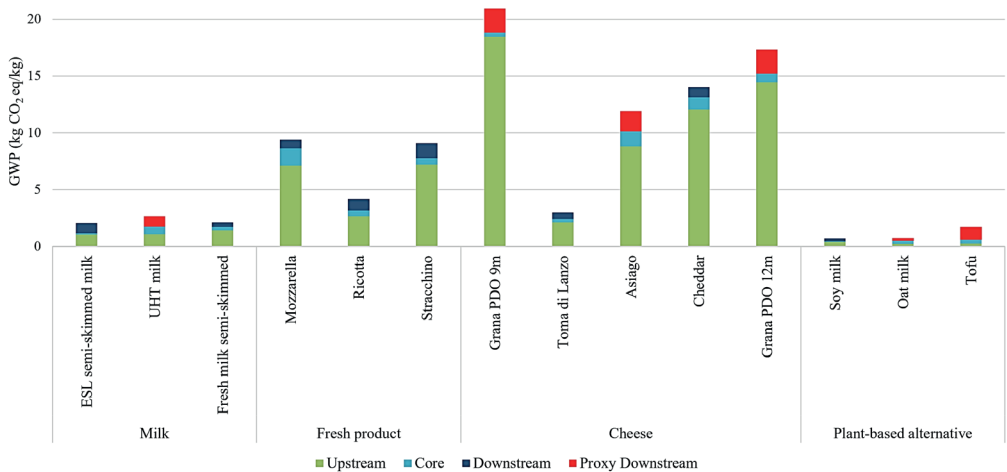


Fig. 2. GWP per kg of product (kg CO₂eq/kg), disaggregated into phases.

Across all dairy products, upstream emissions dominate the overall impact profile. For most products, farm-level emissions account for approximately 75–95 % of total GWP, reflecting the well-known contribution of enteric fermentation, feed production, and manure management within dairy systems.

Fresh milk products display the lowest environmental intensity within the dairy category, with values around 2.0–2.6 kg CO₂eq/kg product. These values are consistent across the ESL, UHT, and fresh milk datasets included in the analysis.

Cheese products exhibit substantially higher GWP values, ranging between 9–20 kg CO₂eq/kg, depending on the product type and maturation level. This increase is primarily explained by the milk concentration effect: several kilograms of milk are required to produce one kilogram of aged cheese. Consequently, upstream emissions accumulate during the transformation process.

Plant-based alternatives show lower absolute impacts per kilogram of product. Plant-based products, Soy milk, oat milk and tofu, display values of approximately 0.72–1.6 kg CO₂eq/kg product, the lowest impact in the products analysed.

These examples illustrate how differences in allocation rules, system boundaries, background databases, and modelling assumptions can lead to variation even for the same product and geographical context. Consequently, cross-study comparisons at the level of individual product values should be interpreted cautiously, the results presented here are therefore intended primarily to highlight category-level patterns rather than precise rankings of environmental performance.

Overall, the results confirm the structural pattern widely observed in food LCA studies: dairy products with higher levels of processing and milk concentration exhibit substantially higher impacts per unit of product mass. However, this mass-based comparison does not account for the functional nutritional role of the different foods, which motivates the normalization approach presented in the following section.

3.2. GWP per NDU

When environmental impact is expressed relative to NDU, the comparative picture shifts substantially. Most importantly, NDU normalization greatly reduces the gap between aged cheeses and plant-based alternatives, but it does not eliminate it.

Fig. 3 reports product-level GWP/NDU values, while Table 2 summarizes the mean value by product category. This indicates that nutritional normalization reduces the apparent disadvantage of cheese observed under the conventional mass-based functional unit.

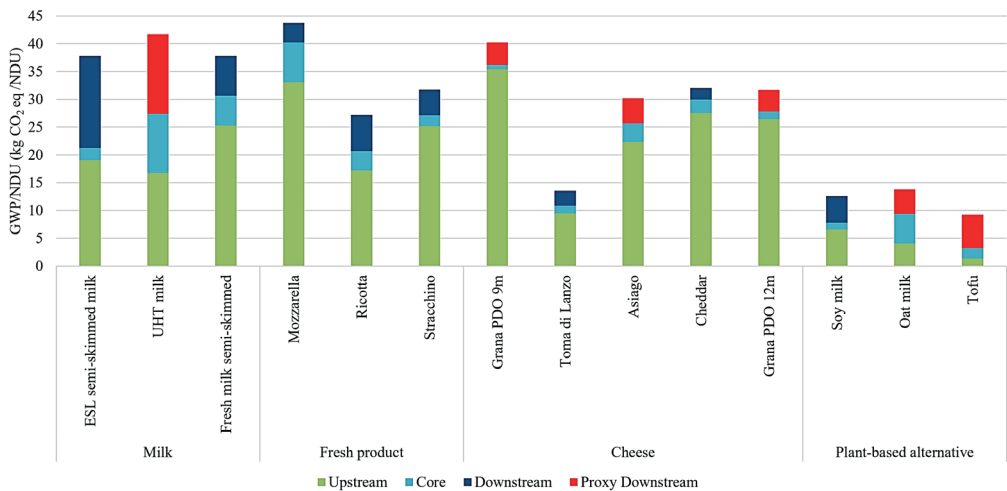


Fig. 3. GWP normalized by Nutritional Density Unit (GWP/NDU).

The shift is explained by the dual nature of cheese production. On the one hand, cheese has a high GWP per kilogram because milk concentration, processing intensity, and ripening increase its environmental burden. On the other hand, the same concentration increases nutritional density, especially in terms of protein and calcium. As a result, when impacts are expressed per unit of nutritional value delivered rather than per product mass, cheese becomes markedly more competitive.

TABLE 2. MEAN GWP, NDU, AND GWP/NDU BY PRODUCT CATEGORY

Product category	Mean GWP/kg	Mean NDU	Mean GWP/NDU
Milk	2.3	0.058	39
Fresh product	7.6	0.22	34
Cheese	13	0.42	30
Plant-based alternative	1.1	0.098	12

The magnitude of this effect is substantial. At category level, the gap between plant-based alternatives and cheese decreases from about thirteen-fold when impacts are expressed per kilogram of product to roughly two-fold when expressed per NDU. Plant-based products therefore remain the best-performing category on average, but the interpretation of dairy products changes considerably once nutritional delivery is considered.

Overall, these results confirm that the choice of functional unit strongly affects comparative sustainability outcomes. A mass-based metric alone assumes equivalence between foods that differ substantially in nutritional role, whereas GWP/NDU captures more effectively the trade-off between environmental burden and nutritional contribution. From this perspective, cheese cannot be interpreted only as a high-impact product per kilogram, but rather as a nutritionally dense food with a significantly improved environmental profile when impacts are related to delivered nutrition.

3.3. Post-Farm Efficiency and Decarbonization Opportunities

Processing was selected as the quantitative focus of the post-farm analysis because it is energy intensive, directly affected by engineering decisions, and supported by sufficiently detailed literature to build simplified decarbonization scenarios [29]. Fig. 4 reports the effect of the considered processing improvement scenarios on GWP/NDU for ESL semi-skimmed milk, UHT milk, mozzarella, and Grana PDO 12 months.

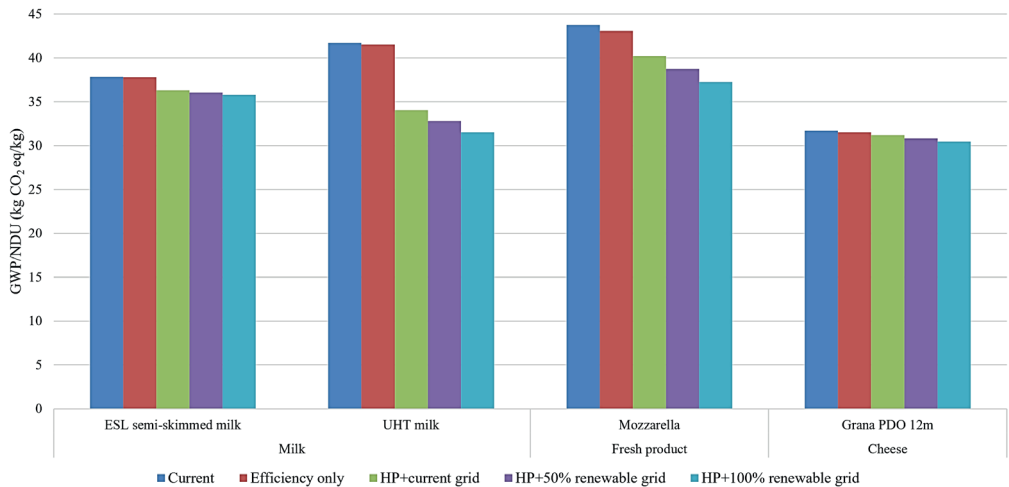


Fig. 4. GWP/NDU under different processing decarbonization scenarios.

Plant-based alternatives were excluded because the objective of this section is to explore decarbonization opportunities within dairy processing, where the largest improvement potential lies.

As shown in Fig. 4, the effect of processing decarbonization is highly product dependent. For ESL semi-skimmed milk, GWP/NDU decreases only marginally, from 38 to 36 in the most ambitious scenario. By contrast, UHT milk shows the strongest response, declining from 42 under current conditions to 34 with heat pump electrification under the current grid, 33 with 50 % renewable electricity, and 32 under near-zero electricity, corresponding to an overall reduction of about 24 % relative to the baseline. Mozzarella shows an intermediate but still substantial improvement, with GWP/NDU decreasing from 44 to 40, 39, and 37 across the three decarbonization scenarios, equivalent to a maximum reduction of about 15 %. Grana PDO 12 m starts from a lower baseline GWP/NDU value, equal to 32, and decreases more moderately to 31, 30.81, and 30, reaching an overall reduction of about 4 %.

These results clarify an important point. The benefit of post-farm decarbonization on total GWP/NDU does not depend only on how strongly the energy system of a product can be improved, but also on the contribution of the improved stage to total product GWP. In the present calculations, only the processing phase was modified. Consequently, products such as UHT milk benefit the most because processing is both thermally intensive and relatively important in the total product footprint. Mozzarella also shows a clear improvement because processing contributes more substantially to total impact than in long-ripened hard cheeses. Grana PDO 12 m, despite its favourable nutritional-density profile, exhibits a smaller overall reduction because the processing contribution in the present dataset remains limited relative to the total footprint, which is still dominated by upstream emissions.

The scenarios should not be interpreted as exhausting the decarbonization potential of post-farm phases. Processing was selected because it offers the clearest basis for quantitative calculation, but additional gains may also arise from improvements in cold-chain distribution, storage, logistics, and waste and by-product management. The present results should therefore be interpreted as a conservative estimate of one specific post-farm lever rather than as an upper bound of total post-farm decarbonization potential.

Read together with Section 3.2, these results suggest that nutritionally dense processed dairy products already perform better than mass-based GWP alone would suggest, and that processing decarbonization can further improve their environmental efficiency per unit of delivered nutrition. More broadly, the whole post-farm system remains an important engineering domain for further environmental improvement.

3.4. Further Analysis

The Table C in Annex reports the results obtained with the simplified NRF-based functional unit and compares them with the GWP/NDU values presented in Section 3.2. Fig. 5 further illustrates the relationship between the two indicators through a scatter plot of GWP/NDU versus GWP/NRF.

The comparison shows that the relative positioning of most products remains broadly stable when the alternative nutritional functional unit is applied. Although absolute values differ between the two indicators, the overall interpretation of environmental efficiency changes only marginally. Products that perform relatively well under GWP/NDU also tend to perform well under GWP/NRF, indicating that the inclusion of a nutrient to limit component does not substantially disrupt the main pattern observed in the analysis. The stability of the main results under this alternative formulation suggests that the category level interpretation is not driven solely by the positive treatment of fat in the NDU indicator.

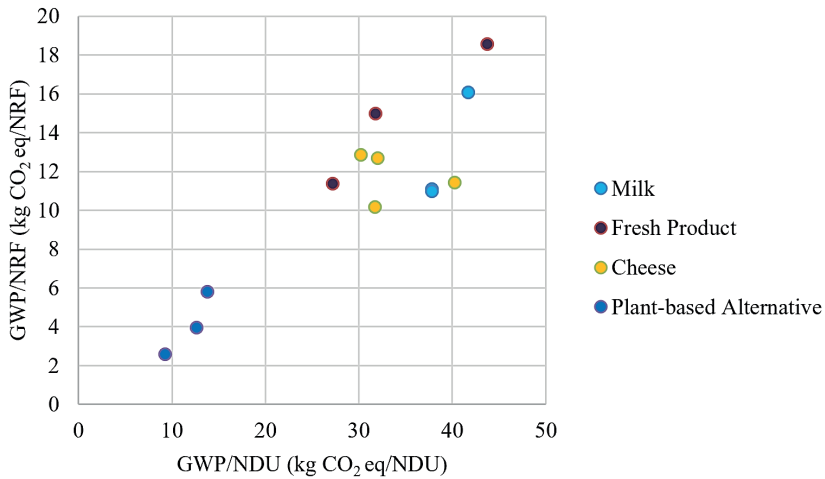


Fig. 5. Relationship between GWP/NDU and GWP/NRF values.

4. DISCUSSION AND CONCLUSIONS

This study integrated EPD-based primary data and peer-reviewed LCA studies into a harmonized cradle-to-grave dataset for fourteen dairy and plant-based products, applied a Nutrient Density Unit functional unit based on energy, protein, fat, carbohydrates, and calcium, and evaluated post-farm processing decarbonization scenarios on nutritionally normalized GWP.

Mass-based results confirm the expected hierarchy: plant-based alternatives show the lowest GWP/kg (0.72–1.6 kg CO₂eq/kg), followed by fluid milk (2.0–2.6), fresh dairy products, and long-ripened cheeses (9–20 kg CO₂eq/kg), with upstream agricultural emissions accounting for 75–95 % of total footprint across all dairy categories. Allocation method alone, as illustrated by the two independent Grana Padano PDO studies in the dataset, can shift reported GWP by over 60 %, reinforcing the need for caution in cross-study product-level comparisons.

Nutritional normalization substantially changes this picture. At category level, mean GWP/NDU values are 39 for milk, 34 for fresh dairy, 30 for cheese, and 12 for plant-based alternatives, reducing the gap between cheese and plant-based products from approximately thirteen-fold to roughly two-and-a-half-fold. Aged cheeses, despite their high mass-based footprint, benefit most from normalization due to their concentrated protein and calcium content. Plant-based alternatives retain a favourable relative position, but the magnitude of their advantage is considerably smaller than mass-based comparisons suggest.

Processing decarbonization scenarios show that heat pump electrification and energy efficiency improvements reduce GWP/NDU by 4–24 % depending on the product. UHT milk is the most responsive due to its thermal intensity, while Grana Padano PDO shows limited sensitivity given the dominance of upstream emissions. The NRF-based robustness check confirms that relative product rankings are broadly stable when fat is included as a nutrient-to-limit.

A key limitation of this study concerns the use of downstream proxy estimations. While these assumptions were necessary to harmonize heterogeneous EPD and LCA sources under a consistent cradle-to-grave scope, they introduce uncertainty and are not sufficiently robust

to support definitive product comparisons. This is because the results are presented and should be interpreted at category level, as comparative patterns across product groups rather than as precise rankings of individual products.

Future work should address three main directions. First, a systematic uncertainty and sensitivity analysis should be conducted to assess the influence of key assumptions on the results, particularly those related to downstream proxy estimation, including distribution, household refrigeration, and packaging end-of-life, as well as the choice and weighting of nutritional metrics. This would allow the robustness of category-level patterns to be tested more explicitly. Second, the application of the full NRF 9.3 index, incorporating nine nutrients to encourage and three nutrients to limit, including saturated fat, added sugar, and sodium, would provide a more complete nutritional characterization, this was not possible in the present study due to incomplete availability of the required nutritional variables across all analysed sources. Third, future research should validate and refine the processing decarbonization scenarios developed in this study through plant and products case studies. By relying on primary inventory data from individual processing facilities, such analyses would allow a more comprehensive assessment of real operational conditions, including facility-level energy audits, heat integration assessments, and country specific electricity mixes. Future developments should also extend the decarbonization analysis beyond processing, by assessing downstream optimization opportunities related to cold-chain refrigeration, logistics, storage, and waste management.

Overall, the results demonstrate that the choice of functional unit is not a methodological detail but a substantive decision with direct implications for sustainability communication and product benchmarking. Processing decarbonization, particularly heat pump integration, coupled with electricity grid decarbonization, represents a concrete and industrially actionable lever to improve the nutritionally adjusted environmental performance of dairy products, and should be prioritized alongside upstream agricultural interventions in sector-level decarbonization strategies.

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REFERENCES

- [1] Crippa M., Solazzo E., Guizzardi D., Monforti-Ferrario F., Tubiello F. N., Leip A. Food Systems Are Responsible for a Third of Global Anthropogenic GHG Emissions. *Nature Food* 2021;2:198–209. <https://doi.org/10.1038/s43016-021-00225-9>.
- [2] Ni H., Zeng H., Liu Z., Li W., Miao S., Yang A., Wang Y. Towards Decarbonizing the Supply Chain of Dairy Industry: Current Practice and Emerging Strategies. *Carbon Neutrality* 2025;4:8. <https://doi.org/10.1007/s43979-025-00124-z>.
- [3] Lazenby J. W., Tovar M., Koen A. Case Study: Electrification and Thermal Energy Storage in the Dairy Industry. Future Cleantech Architects: Remscheid, Germany, 2025.
- [4] Arabska E. From Farm to Fork: Human Health and Well-Being through Sustainable Agri-Food Systems. *Journal of Life Economics* 2021;8:11–27. <https://doi.org/10.15637/jlecon.8.1.02>.
- [5] International Organization for Standardization (ISO) ISO 14040:2006, Environmental Management – Life Cycle Assessment – Principles and Framework. 2006:14040:20.
- [6] Finnegan W., Yan M., Holden N. M., Goggins J. A Review of Environmental Life Cycle Assessment Studies Examining Cheese Production. *The International Journal of Life Cycle Assessment* 2018;23:1773–1787. <https://doi.org/10.1007/s11367-017-1407-7>.

- [7] Moja A. I., Canja C., Pădureanu V., Andreea R., Calefariu G. Environmental Impact Assessment of Cheese Production: A Systematic Review of Life Cycle Assessment Studies. *Journal of Agroalimentary Processes and Technologies* 2025.
- [8] Bava L., Bacenetti J., Gislon G., Pellegrino L., D'Incecco P., Sandrucci A., Tamburini A., Fiala M., Zucali M. Impact Assessment of Traditional Food Manufacturing: The Case of Grana Padano Cheese. *Science of The Total Environment* 2018;626:1200–1209. <https://doi.org/10.1016/j.scitotenv.2018.01.143>
- [9] Kovanen I., Kytä V., Kärllund A., Pajari A.-M., Tuomisto H., Saarinen M., Kolehmainen M. Advancing Methods for Comparative Nutritional LCA of Milk and Plant-Based Milk Substitutes. *The International Journal of Life Cycle Assessment* 2025;30:462–476. <https://doi.org/10.1007/s11367-024-02407-6>
- [10] Herrmann M., Mehner E., Egger L., Portmann R., Hammer L., Nemecek T. A Comparative Nutritional Life Cycle Assessment of Processed and Unprocessed Soy-Based Meat and Milk Alternatives Including Protein Quality Adjustment. *Front. Sustain. Food Syst.* 2024;8. <https://doi.org/10.3389/fsufs.2024.1413802>
- [11] Silva B. Q., Smetana S. Review on Milk Substitutes from an Environmental and Nutritional Point of View. *Applied Food Research* 2022;2(1):100105. <https://doi.org/10.1016/j.afres.2022.100105>
- [12] Ladha-Sabur A., Bakalis S., Fryer P. J., Lopez-Quiroga E. Mapping Energy Consumption in Food Manufacturing. *Trends in Food Science & Technology* 2019;86:270–280. <https://doi.org/10.1016/j.tifs.2019.02.034>
- [13] Lombardi P. A., Wasser H. P., Pantaleo A. M. Flexibility Exploitation in Net-Zero Energy Factories. A Technical and Economic Study Case for Dairy Systems Located in Central and South Europe. *Renewable Energy* 2024;234:121197. <https://doi.org/10.1016/j.renene.2024.121197>
- [14] Malliaroudaki M. I., Watson N. J., Ferrari R., Nchiri L. N., Gomes R. L. Energy Management for a Net Zero Dairy Supply Chain under Climate Change. *Trends in Food Science & Technology* 2022;126:153–167. <https://doi.org/10.1016/j.tifs.2022.01.015>
- [15] Nunes J., Silva P. D., Andrade L. P., Gaspar P. D., Cuce P. M., Cuce E., Yilmaz Y. N. Energy Efficiency in Portuguese Traditional Cheese Industries: A Comprehensive Case Study. *Energies* 2025;18(3):562. <https://doi.org/10.3390/en18030562>
- [16] González-García S., Castanheira É. G., Dias A. C., Arroja L. Using Life Cycle Assessment Methodology to Assess UHT Milk Production in Portugal. *Science of The Total Environment* 2013;442:225–234. <https://doi.org/10.1016/j.scitotenv.2012.10.035>
- [17] Ferronato G., Tobanelli N., Bani P., Cattaneo L. Carbon Footprint Assessment of Dairy Milk and Grana Padano PDO Cheese and Improvement Scenarios: A Case Study in the Po Valley (Italy). *Animals* 2025;15(6):811. <https://doi.org/10.3390/ani15060811>
- [18] Verduna T., Blanc S., Merlino V. M., Cornale P., Battaglini L. M. Sustainability of Four Dairy Farming Scenarios in an Alpine Environment: The Case Study of Toma Di Lanzo Cheese. *Front. Vet. Sci.* 2020:7. <https://doi.org/10.3389/fvets.2020.569167>
- [19] Dalla Riva A., Burek J., Kim D., Thoma G., Cassandro M., De Marchi M. The Environmental Analysis of Asiago PDO Cheese: A Case Study from Farm Gate-to-Plant Gate. *Italian Journal of Animal Science* 2018;17:250–262. <https://doi.org/10.1080/1828051X.2017.1344936>
- [20] Gosalvitr P., Cuellar-Franca R., Smith R., Azapagic A. Energy Demand and Carbon Footprint of Cheddar Cheese with Energy Recovery from Cheese Whey. *Energy Procedia* 2019;161:10–16. <https://doi.org/10.1016/j.egypro.2019.02.052>
- [21] LCA of Oatly Barista for Denmark, Norway, Belgium, Italy and Spain, and Comparison with Cow's Milk 2024.
- [22] Colimoro M., Ripa M., Santagata R., Ulgiati S. Environmental Impacts and Benefits of Tofu Production from Organic and Conventional Soybean Cropping: Improvement Potential from Renewable Energy Use and Circular Economy Patterns. *Environments* 2023;10(5):73. <https://doi.org/10.3390/environments10050073>
- [23] Cottafava D., Brussa G., Cavenago G., Cespi D., Rigamonti L., Bala A., Beigbeder J., Refalo P., Szadovskii I. Requirements for Comparative Life Cycle Assessment Studies for Single-Use and Reusable Packaging and Products: Recommendation for Decision and Policy-Makers. *Int J Life Cycle Assess* 2024;29:909–911. <https://doi.org/10.1007/s11367-024-02291-0>
- [24] Sonesson U. *Food Production and Emissions of Greenhouse Gases: An Overview of the Climate Impact of Different Product Groups*; SIK - Institutet för livsmedel och bioteknik: Göteborg, 2010.
- [25] McAuliffe, G.A.; Takahashi, T.; Lee, M.R.F. Applications of Nutritional Functional Units in Commodity-Level Life Cycle Assessment (LCA) of Agri-Food Systems. *The International Journal of Life Cycle Assessment* 2020;25:208–221. <https://doi.org/10.1007/s11367-019-01679-7>
- [26] Muehlhoff E., Bennett A., McMahon D. *Milk and Dairy Products in Human Nutrition*; FAO: Rome, 2013.
- [27] Regulation (EU) no 1169/2011 of the European Parliament and of the Council.
- [28] Drewnowski A., Fulgoni V. L. Nutrient Density: Principles and Evaluation Tools. *Am J Clin Nutr* 2014;99:1223S–8S. <https://doi.org/10.3945/ajcn.113.073395>
- [29] Nunes J., Andrade L. P., C., D. Opportunities for the Energy Efficiency Improvement in the Dairy Food Sector – the Case Study of Portuguese Traditional Cheese Industries. Yokohama, Japan.

ANNEX

TABLE A. PRODUCTS ANALYSED AND DATA SOURCES

Product Category	Product	Data source	Background databases	Type of study	System boundary
Milk	ESL semi-skimmed milk	EPD International	Ecoinvent 3.9.1; Agri-footprint 6	EPD	Cradle-to-grave
	UHT milk	[16]	Ecoinvent 2.0 e 2.1;	LCA study	factory gate
	Fresh milk, semi-skimmed	EPD International	Agri-footprint 5.0; Agribalyse v.1.31	EPD	Cradle-to-grave
Fresh Product	Mozzarella	EPD International	Ecoinvent 3.9.1; Agri-footprint 6	EPD	Cradle-to-grave
	Ricotta	EPD International	Ecoinvent 3.9.1; Agri-footprint 6	EPD	Cradle-to-grave
	Stracchino	EPD International	Ecoinvent 3.9.1; Agri-footprint 6	EPD	Cradle-to-grave
Cheese	Grana PDO 9 months	[17]	Ecoinvent 3.8 e 3.9.1; Agri-footprint 5	LCA study	Factory gate
	Toma di Lanzo	[18]	Ecoinvent 3	LCA study	retailer gate
	Asiago	[19]	Ecoinvent 3.1	LCA study	Cradle-to-grave
	Cheddar	[20]	Ecoinvent 3.3 and 2.2	LCA study	Cradle-to-grave
	Grana PDO 12 months	[8]	Ecoinvent 3	LCA study	Factory gate
Plant-based alternative	Soy milk	EPD International	Ecoinvent 3.6; Agri-footprint 5	EPD	Cradle-to-grave
	Oat milk	[21]	Ecoinvent 3.9; Agri-footprint 3.6 and 6.3	LCA study	consumer gate
	Tofu	[22]	Ecoinvent 3.1	LCA study	Factory gate

TABLE B. NUTRITIONAL VALUES USED FOR NDU CALCULATION

Product	Energy, kcal	Fat, g	Carbohydrates, g	Protein, g	Calcium, mg	NDU
ESL semi-skimmed milk	46.6	1.6	5.0	3.1	116.5	0.050
UHT milk	63.0	3.6	4.7	3.3	120.0	0.057
Fresh milk, semi-skimmed	47.4	1.5	4.9	3.5	116.1	0.052
Mozzarella	214.0	16.0	1.0	16.5	324.0	0.195
Ricotta	144.0	11.0	3.5	7.7	295.0	0.139
Stracchino	269.0	24.0	1.2	12.0	567.0	0.260
Grana PDO 9 months	398.0	29.0	0.0	33.0	1165.0	0.509

Toma di lanzo	337.4	28.8	0.5	26.2	N/A	0.190
Asiago	368.0	30.0	0.5	24.0	700.0	0.359
Cheddar	388.0	31.0	0.5	26.7	810.0	0.401
Grana PDO 12 months	398.0	29.0	0.0	33.0	1165.0	0.509
Soy milk	48.0	2.3	3.5	3.3	120.0	0.053
Oat milk	61.0	3.0	7.1	1.1	120.0	0.049
Tofu	115.0	7.0	0.5	16.0	350.0	0.173

TABLE C. COMPARISON BETWEEN GWP/NDU AND GWP/NRF RESULTS

Product Category	Product	GWP/NDU	GWP/NRF	Δ%
Milk	ESL semi-skimmed milk	38	11	−71 %
	UHT milk	42	16	−61 %
	Fresh milk semi-skimmed	38	11	−71 %
Fresh Product	Mozzarella	44	19	−58 %
	Ricotta	27	11	−58 %
	Stracchino	32	15	−53 %
Cheese	Grana PDO 9 months	40	11	−72 %
	Asiago	30	13	−57 %
	Cheddar	32	13	−60 %
	Grana PDO 12 months	32	10	−68 %
Plant-based alternatives	Soy milk	13	4	−69 %
	Oat milk	14	6	−58 %
	Tofu	9	3	−72 %