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Is organic farming truly sustainable? Estimating the environmental milk costs of Italian alpine dairy farms

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ABSTRACT

Most studies on dairy farming's environmental impacts have utilized Life Cycle Assessment (LCA), focusing on emissions quantification within advantaged regions. However, monetizing these emissions offers a more precise and comparable framework for evaluating different farming systems. This study aims to estimate the true costs of milk production by assessing both the economic and environmental impacts of organic (ORG) and conventional (CON) Simmental dairy farming systems. We expanded the Typical Farm Approach (TFA), a representative farm model, by including 15 ORG farms and 15 CON farms. Using LCA methodology, six environmental impact categories were evaluated: Global Warming Potential (GWP_{100}), Acidification Potential (AP), Marine Eutrophication Potential (MEP), Terrestrial Ecotoxicity (TE), Land Use (LU), and Water Consumption (WC). Two functional units were employed: square meters of farm area and kilograms of energy-corrected milk (ECM). Results reveal that although ORG farms incur higher operating costs due to an unfavorable milk-to-feed price ratio, they generate higher revenues and show statistically insignificant differences in fixed and total costs per kg ECM compared to CON farms, while also benefiting from higher returns from additional subsidies. The estimated environmental costs range from 43 to 64 euro cents per kg ECM for ORG farms and 37 to 51 euro cents per kg ECM for CON farms. Among the impact categories, GWP100 (up to 52 %) and LU (up to 59 %) account for the largest shares in the sensitivity analysis of total environmental costs. However, despite these findings, the internalization of environmental costs remains impractical due to uncertainties in accurately assessing environmental impacts across various farming practices, regions, and methods. Our analyses suggest that optimizing farm productivity and efficiency would offer greater economic and environmental benefits compared to switching from CON to ORG farms.

1. Introduction

Dairy farming systems face the challenge of meeting the growing demand for milk while addressing pressing environmental concerns and ensuring economic sustainability for farmers. While farmers in lowland areas benefit from better access to farmland and greater flexibility to expand herd sizes, mountain farmers are constrained by climatic, topographic and agronomic disadvantaged areas, often resulting in limited land availability [1,2]. In response to these challenges, mountain farmers may adopt dual-purpose breeds [3] or increasing productivity through higher concentrate feed inputs [2] imported form other regions/countries. Additionally, consumer demand for organic products, which require fewer resources such as water and energy per unit of land, presents an opportunity to shift dairy systems toward more sustainable practices [4,5]. In 2023, per capita consumption of organic products was 17.0 euros, with Switzerland leading at 468 euros, followed by Denmark (362 euros) and Austria (292 euros). Meanwhile, global organic agricultural land covered 98.9 million hectares, representing 2.1 % of total agricultural land, marking an expansion of 2.5 million hectares (2.6 %) [6]. This shift is supported by the European Union's Farm to Fork strategy, which aims to expand organic farming to cover 25 % of the EU's agricultural area by 2030 [7].

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On one hand, organic farming is often criticized for lower yields and higher land use, assuming agriculture's sole goal is to maximize yield, without considering the environmental costs of conventional farming [8]. Environmental costs refer to the ecological damage caused by production processes not reflected in market prices, yet borne by polluters and consumers [9]. True Cost Accounting (TCA) has emerged as a promising tool for internalizing hidden costs through the integration of environmental assessments and cost analysis [10,11]. TCA applies monetary valuation to Life Cycle Assessment (LCA) results, helping to better quantify and compare the true costs of agricultural products [12]. While LCA is widely used, it often shows significant variability across studies, favoring high-input systems, which limits cross-study comparisons [9,13]. For instance, organic dairy farming typically has a lower or comparable carbon footprint per unit of milk, particularly when accounting for soil carbon sequestration and reduced synthetic fertilizer use [14]. However, other studies show no significant difference in greenhouse gas emissions per kg of milk, with organic systems performing better per unit of land area [15]. These discrepancies in study design and context contribute to uncertainties in monetizing environmental impacts. Given these complexities, we assess the economic performance gap between organic and conventional farms across various income scenarios, emphasizing the need to consider the financial viability of organic farming for its adoption [16]. Study showed that conventional farmers are concerned about the costs and benefits of transitioning to organic practices [17], making economic performance benchmarking crucial to prevent financial distress and missed opportunities [18].

This study aims to estimate the true costs of milk production by assessing both the economic and environmental impacts of organic and conventional Simmental dairy farming systems. The environmental impacts of these systems are monetized, aggregating various environmental factors into a single, comparable unit. This unit converts complex environmental metrics into a universal economic value, allowing for easier comparisons across different farming systems. To the best of our knowledge, this is the second study to monetize the environmental costs of dairy farms using LCA in the Alpine region. However, compared to the study by Antony et al. [9], our analysis provides a detailed cost-revenue economic evaluation and incorporates environmental impact assessments, such as water consumption and marine eutrophication, while excluding human toxicity, as these impacts are more contextually relevant to the specific farming practices studied in South Tyrol. Moreover, this study adopts the term TCA rather than Environmental Life Cycle Costing (E-LCC), differing from Hunkeler et al. [19], consistent with reports by CE Delft [20], True Price Foundation [21], and Antony et al. [9]. While both methodologies can be combined with LCA, LCC methodology has only been standardized for petroleum, gas, buildings and constructed assets [22]. The environmental cost rates in this study account for damage costs, such as those from soil and air pollutants, water use, and land use change (considered social costs), which are often overlooked in E-LCC calculations. For instance, Ruviaro et al. [23] used LCC to estimate the environmental costs of dairy production systems, focusing solely on greenhouse gas emissions. Review studies have found that many authors did not label their methods as LCC and identified inconsistencies in the methodological approaches [22,24].

To evaluate environmental impacts and cost analysis, we employ matching methods for comparing organic and conventional systems, as discussed in the literature [14,25]. Earlier studies overlooked farmer heterogeneity and selection bias, often treating conventional farms as counterfactuals, which led to incorrect evaluations due to confounding effects of farm characteristics and climate [26]. Self-selection bias is evident in studies on organic and conventional dairy farming in Switzerland [27] and Norway [25]. While matching methods address non-randomization in observational studies [28], recent research warns that they may increase imbalance and bias [14]. Optimal results depend on aligning model assumptions with data generation and selecting appropriate analytic strategies, such as propensity scores [29], marking an advancement over earlier studies that treated observational data as randomized trials.

The remainder of this paper is organized as follows: Section 2 outlines the methodology, Section 3 presents the results and discussion, with subsections 3.1 detailing farm characteristics, 3.2 discussing farm input-output, 3.3 estimating economic performance, 3.4 assessing environmental impacts, 3.5 estimating environmental costs, and Section 6 provides the conclusion.

2. Methods

2.1. Study design and materials

South Tyrol, an alpine province in northern Italy bordering Austria and Switzerland (Fig. 1), is characterized by a strong focus on grassland-based livestock farming. Approximately 61,332 ha of grassland are harvested for feed, while 127,216 ha are used as mountain pastures [30]. Dairy cattle farming is the predominant livestock system, with 4105 farms averaging 15 dairy cows each [31]. The main breeds include Simmental and Brown Swiss, each comprising about 30 percent of the total dairy herd, followed by Holstein Friesian at around 20 percent. The remaining share consists of traditional local breeds such as Alpine Grey and Pinzgauer [30]. In 2023, total milk production in South Tyrol reached 362.5 million kilograms, of which 4.4 percent, or 15.9 million kilograms, were produced under certified organic conditions [32].

We extended the Typical Farm Approach (TFA) [33], which encompasses specific production systems, farm sizes, technology levels, and average milk outputs in a dairy region. TFA is based on the "representative firm" concept, originally introduced by Alfred Marshall and later expanded by Frank Taussig in the early 20th century [34,35]. Both scholars employed this concept to develop the framework for determining the "normal cost of production" [36]. Unlike the standard TFA, which relies on a single dataset from a panel of 1–5 farmers, an advisor, and a scientist, our study employed 15 dairy farms to represent each production system, emphasizing herd and land use uniformity. This expert-based approach was necessitated by the general lack of economic statistics on production systems in existing agricultural data [36]. In collaboration with South Tyrolean breeders' associations, local dairy farms, and researchers from the Free University of Bozen-Bolzano, we established criteria for TFA in South Tyrol and selected Simmental cattle as the region's dominant breed. Data were collected between May and October 2023, reflecting the agricultural input-output and economic conditions of 2022 (see sections 3.1, 3.2 and 3.3). Given the voluntary participation, data collection was finalized at 17 organic (ORG) farms when it became evident that further data from additional farmers would not contribute new information. However, only 15 of the ORG farms met the criteria. We also included 15 conventional (CON) farms as counterfactual, which had average annual milk yields exceeding 8000 kg per cow and minimal pasture access, while ORG farms provided seasonal grazing as mandated by EU regulations [37]. Since the 2000s, the application of TFA in farm economic analysis has increased, focusing more on results than on the applicability of the approach or the justification for its use [36].

2.2. Life cycle assessment approach

2.2.1. Goal and scope

A cradle-to-farm gate approach was employed for the Life Cycle Assessment (LCA), without applying any allocation method for calves or rearing processes (Fig. 2). The assessment of midpoint environmental impacts was conducted using the commercial software openLCA version 2.0.1, utilizing the Agribalyse database version 3.0.1 and the ReCiPe Midpoint (H) method [39]. The methodological choices in this study followed the guidelines set by the International Organization for Standardization (ISO) 14040 and ISO 14044. The selection of impact categories followed the guidelines for reporting the Product Environmental

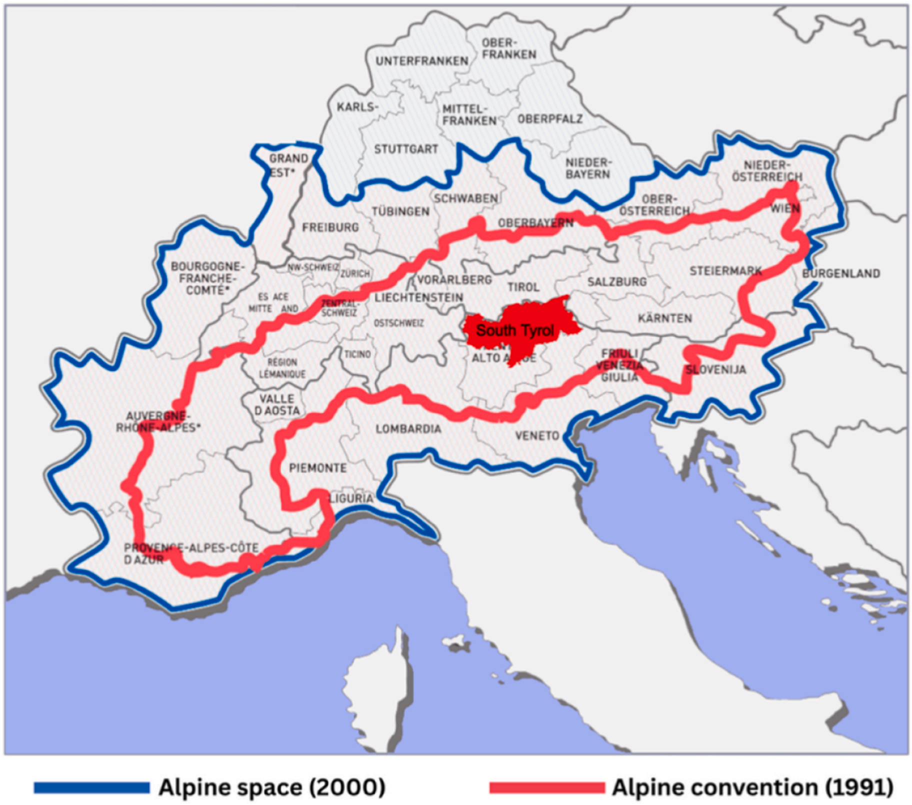

Fig. 1. Location of the studied in the Apline region. Modified from [38].

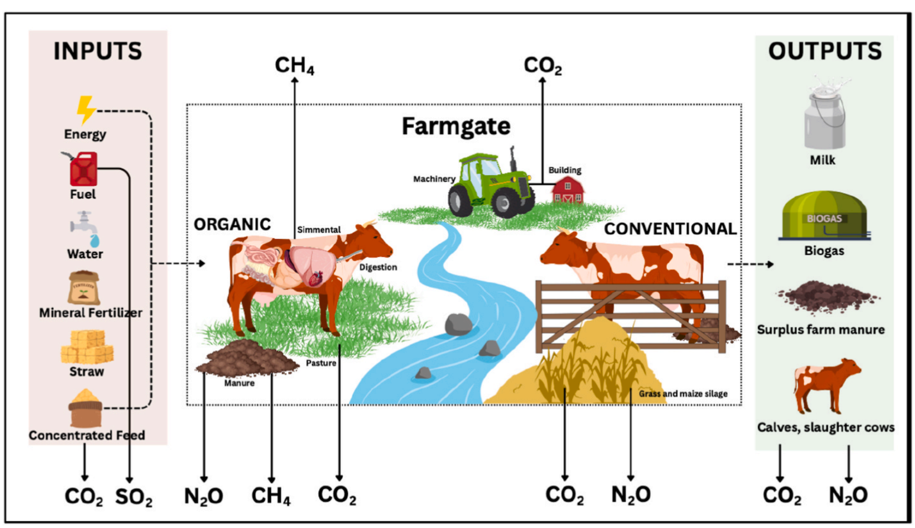

Fig. 2. System boundaries chart for ORG and CON dairy farming system.

Footprint (PEF) of dairy products [40]. In accordance with recommendations from the International Dairy Federation [41], two functional units (FU) were applied: kilograms of energy-corrected milk (ECM) and square meters of farm area. The first FU was 1 kg of ECM, calculated using the formula by Sjaunja et al. [42]: 1 kg of raw milk $\times$ (0.25 + 0.122 $\times$ Fat % + 0.077 $\times$ Protein %). The second FU was 1 m^2 of agricultural land based on the area required for on-farm feed production for each system [43]. However, the monetization of environmental impacts was carried out solely based on the kilogram of ECM.

2.2.2. *Life cycle inventory and impact assessment*

Calculations considering all inputs and outputs related to the functional unit (from cradle to farm-gate) were performed for each system conducting the similar methods by Zanon et al. [43]. We applied six impact categories: global warming potential (GWP_{100}; in kg CO_2 equivalents [CO_2-eq], 100-year horizon, with characterization factors of 27.5 for CH_4 and 265 for N_2O; IPCC (Intergovernmental Panel on Climate Change) [44], acidification potential (AP; in kg SO_2 equivalents [SO_2-eq]), marine eutrophication potential (MEP; in N equivalents [N-eq]), terrestrial ecotoxicity (TE; in 1,4-dichlorobenzene [1,4-DCB]), water consumption (WC; in m^3), and land use (LU; CML-IA non-baseline V3.06/EU25 method; [45], expressed in square meters per year (m^2/year crop-eq), indicating land occupation [46]. The LU includes the agricultural area used to produce feed, both upstream of the farm and on the farm (see section 3.4).

2.2.3. Emission factors

Emissions for all farms were calculated using the methodology outlined by the IPCC [47] to assess the relationship between gross energy intake (GEI) and emissions from enteric fermentation. CH_4 emissions from enteric fermentation, manure storage, and direct deposition on grasslands were estimated using the Tier 2 IPCC equation. A methane conversion factor (Ym) of 4 % for fattening cattle and 6.5 % for adult cows and bulls was applied. Methane emissions from manure volatile solids (VS) were calculated at 3.9 kg per animal per day, with a maximum production potential of 0.1 m^3/kg VS. For N_2O emissions, calculations followed the IPCC guidelines, with specific emission factors for manure and direct nitrogen deposition on soil, including values for nitrate leaching and runoff based on Italian-specific data. CO_2 emissions from energy use were calculated based on diesel (liters) and electricity (kilowatt-hours; kWh) consumption, using emission factors from Romano et al. [48], including a diesel density of 0.85 kg per liter and 3.14 kg CO_2 eq per kg of diesel burned. The characterization factors for GWP_{100} were 1, 34, and 298 CO_2 eq for CO_2, CH_4, and N_2O, respectively, as recommended by Huijbregts et al. [39]. Further equation can be found in Annex 1.

2.3. Economic calculations

Following the cost structure outlined by Kühl et al. [2], operating costs included feedstuffs, veterinary and artificial insemination expenses, as well as dairy-related costs such as hoof care, testing, animal transport, straw bedding, water and wastewater, energy, and machinery and building upkeep (see section 3.3). The cost of homegrown feed was derived from the estimation provided by Peratoner et al. [49], as this study is specifically focused on estimating forage production costs in South Tyrol. The study developed a cost model by summing machinery-related, personnel-related, contractor, and other expenses (including fence repair materials, pasture troughs, salt blocks, and silage costs), while adjusting for altitude, slope, and forage production. Since the altitude and slope of the pastureland remain constant, we only adjusted the forage-related costs for each farm surveyed. Notably, mountainous pasture land requires specific calculations, particularly with respect to the effects of slope gradient and altitude ([49]. Fixed costs encompassed building construction or renovation and investments in machinery, with amortization periods of 30 years for farm buildings and 15 years for agricultural machinery. Herd renewal costs included the purchase of animals, as well as additional expenses such as insurance, consulting fees, and the opportunity cost of unpaid family labor. The working time for daily tasks was estimated based on Poulopoulou et al. [50], with 164.2 h per cow per year for tie-stall farms and 112.6 h for loose housing farms, which were multiplied by a standard agricultural wage of €15.75 per hour [51]. Farm-specific milk prices were calculated using the default milk prices (CON or ORG) provided by the dairy cooperative, along with adjustments for bonus or deduction payments based on milk quality (i.e., protein, fat, and somatic cell count). Cattle sales and subsidies were also included in the revenue calculation. The return analysis was conducted across five levels, providing clear information to draw conclusions on economic viability (see Section 3.3.).

2.4. Environmental costs

True Cost Accounting (TCA) is performed by monetizing the Life Cycle Assessment (LCA) results, which are presented as impact indicators, using established cost rates [11]. Due to limitations in monetizing all environmental impacts comprehensively, sensitivity analyses were conducted to address the resulting uncertainties. Further, no cost rates were developed as part of this study. Instead, this study utilizes three cost rates from two key sources: *the Environmental Prices Handbook* [20] and *Monetization Factors for True Pricing* [21], both of which provide EU-wide environmental cost rates (Annex 2). The range of cost rates in the literature is mostly due to uncertainties (Annex 3). It is important to note that due to unavailability of environmental cost rates for Italy, cost rates from studies with different reference years or countries are adjusted to reflect values for Italy in 2022 ($_{€2022}$) using a "value transfer" method. This method adjusts for variations in income levels, purchasing power parity (PPP), and price levels by using the average income, adjusted for how income is distributed across individuals. Based on study of Antony et al. Antony et al. (2021), the formula for this adjustment is as follows:

$$C_{PPP-corrected} = CB \times \left(\frac{YI}{YN}\right)^{e} \tag{1}$$

Where $C_{PPP\text{-}corrected}$ represents the cost rate for Italy, *CB* is the cost rate from the baseline study (this study used Netherlands rates as a benchmark), *YI* is the PPP-weighted per capita income for Italy, *YN* is the PPP-weighted per capita income for the baseline country (Netherlands), and e denotes the income elasticity of willingness to pay, with an elasticity value of 1.0 being used. In cases where cost rates reference years other than 2022 (the reference year used in this study), they must be corrected to the 2022 price level using the harmonized consumer price index (HICP). This correction is carried out using the following formula:

$$C_{HP-corrected} = CB \times \left(\frac{Ir}{Ib}\right) \tag{2}$$

Where $C_{HP\text{-}Corrected}$ is the cost rate for the desired reference year r, *CB* is the cost rate for the baseline reference year *b*, *Ir* represents the HICP of the reference year *r*, and *Ib* is the HICP of the reference year *b* from the baseline study.

The monetary evaluation for each impact was then aggregated to determine total environmental costs per farming system, enabling comparisons across different milk farming systems. Environmental costs in this study are monetized using the damage cost approach, as market prices for environmental goods are not directly observable. In LCA, characterization factors standardize emissions and substances within each impact category, allowing for the comparison and aggregation of environmental impacts. Monetizing individual emissions is challenging due to the lack of valid cost rates and the impracticality of managing large numbers of substances [9]. Therefore, monetization is consistently performed at the environmental Mid-Point impact level.

2.5. Data analysis

Most comparisons of environmental and, to a lesser extent, economic performances of organic farming do not control for the self-selection of organic farms and the potential structural differences between organic and conventional farms [52]. This study used propensity score matching (PSM) to address selection bias between ORG and CON dairy farms, following Lambotte et al. [14]. A probit regression model was estimated with farm type (organic = 1, conventional = 0) as the dependent variable, and covariates including dairy herd size, population distribution, total land area, barn type, elevation, farming workload, and depreciation of buildings and machinery as proxies for technology adoption (Table 1). Nearest neighbor matching was implemented using the psmatch2 package in STATA 17. This study presents analyses at two main phases: before matching and after matching. Following the adequate validation of the data's normality using the Shapiro-Wilk test, the dataset prior to matching was analyzed with a *t*-test. The before matching analysis reveals raw differences, highlighting the need to control for confounding variables, while the Average Treatment Effect on the Treated (ATT) analysis provides causal estimates of organic farming's impact, mitigating selection bias and strengthening the validity of conclusions on milk production, economic performance, and environmental outcomes.

Table 1
Probit regression results for the propensity score estimation of the adoption of CON and ORG farming systems (n = 15, respectively).

Farm characteristic (covariates)	Odds ratio	S.E.	*Z*	*P*-value
Cow lactation (head)	−3.778	2.588	−1.46	0.144
Calves <6 month (head)	−1.772	1.075	−1.65	0.099
Calves 6–24 month (head)	−2.562	1.779	−1.44	0.150
Total dairy (LU)	3.778	2.579	1.46	0.143
Total land (ha)	−0.069	0.059	−1.16	0.245
Barn type (dummy 1 = tied; 0 = freestall)	−0.098	1.119	−0.09	0.930
Elevation (m a.s.l.)	0 0.003	0 0.002	1.74	0.081
Unpaid labour cost (€/kg ECM)	−0.003	1.263	−0.00	0.998
Depreciation of building (€/LU)	0.001	0.001	0.62	0.532
Depreciation of machinery (€/LU)	−0.001	0.001	−0.54	0.589
Constant	−2.747	2.183	−1.26	0.208
Sample size (N) = 30; LR chi2 (10) = 13.67; Loglikelihood = −13.961; Pseudo R^2 = 0.329				

The current propensity score matching model shows a moderate fit, with *t*-test results indicating no significant differences between the treated and control groups for most covariates (Table 2), suggesting an improved balance, though not perfect. The mean bias of 31.0 % is within an acceptable range for exploratory analysis, and while some variance ratios, such as for unpaid labour cost, fall outside the ideal range, this does not undermine the analysis. The balance value exceeding 25 % suggests room for improvement, but the results remain justifiable for continued analysis. Propensity score weighting effectively mitigated pre-matching differences between ORG and CON groups, validating the common support assumption and ensuring sufficient structural similarity for reliable ATT simulation, as shown by the improved post-matching balance (Table 2).

3. Results and discussion

3.1. Farm characteristics

Table 1 presents the results of the probit regression analysis used to estimate propensity scores between CON and ORG dairy farms (n = 15 per group). None of the farm characteristics were significant predictors ($p < 0.05$). However, the number of calves under six months of age (OR = −1.772, p = 0.099) and farm elevation (OR = 0.003, p = 0.081) approached marginal significance ($p < 0.10$). Other variables including cow lactation stage (OR = −3.778, p = 0.144), number of calves aged 6–24 months (OR = −2.562, p = 0.150), total dairy livestock units (OR = 3.778, p = 0.143), and land area (OR = −0.069, p = 0.245) showed no significant association with dairy system classification. These results indicate that the matching process yielded a reasonably balanced sample, with farm structural characteristics showing limited influence on farm type, and that farmer-specific factors may play a more substantial influence in this context.

Table 2
Testing of covariate balance using the propensity score (evaluation of quality of match).

Farm characteristic (covariates)	Samples[1]	Mean		*t*-test	V(T)/V (C)[2]
		CON	ORG		
Cow lactation (head)	Before	17.50	14.20	−1.38	
	After	20.50	15.20	−1.40	1.36
Calves <6 month (head)	Before	3.70	2.40	−1.72	
	After	2.60	2.20	−0.50	1.38
Calves 6–24 month (head)	Before	4.70	3.90	−0.76	
	After	3.10	4.50	1.01	1.32
Total dairy (LU)	Before	22.30	18.00	−1.46	
	After	23.77	19.23	−1.14	2.94
Total land (ha)	Before	18.20	14.10	−1.54	
	After	13.03	15.36	0.84	1.44
Elevation (m a.s.l.)	Before	1147.70	1218.10	0.88	
	After	1158.10	1206.20	0.65	3.58
Unpaid labour cost (€/kg ECM)	Before	0.20	0.38	1.02	
	After	0.15	0.21	1.11	4.64
Depreciation of building (€/LU)	Before	420.45	687.08	2.15**	
	After	703.88	607.68	−0.44	0.26
Depreciation of machinery(€/LU)	Before	576.19	531.09	−0.35	
		635.87	592.60	−0.25	2.09
LR X^2	27.73				
Mean Bias	31.0				
MedianBias	25.2				

Analysis of farm characteristics before and after matching revealed several non-significant differences between CON and ORG farms. Before matching, CON farms tended to have larger herds (17.50 vs. 14.20 lactating cows), more calves, higher total dairy livestock units (22.30 vs. 18.00), and larger land areas (18.20 ha vs. 14.10 ha), although these differences were not significant (Table 2). ORG farms were generally located at higher elevations and incurred greater unpaid labor costs. The only significant difference observed before matching was in building depreciation per livestock unit, which was higher on organic farms (€687.08/LU vs. €420.45/LU). After matching, some variance ratios remained notably distant from 1 (Table 2), particularly for elevation and unpaid labor cost. This may reflect greater farm heterogeneity in mountainous regions due to varying landscape conditions, as well as differences in economies of scale and productivity affecting labor inputs. However, most covariates achieved acceptable balance, indicating comparable distributions between matched groups.

Overall, our farm's characteristics align with Lambotte et al. [14], which emphasizes the importance of homogeneity and equal counterfactual farms when comparing environmental and economic performance between CON and ORG dairy systems. Bijttebier et al. [53] also reported that ORG and CON farms can be similar in land base and herd size in some cases, although ORG farms tend to be smaller than CON farms in Europe. While farm characteristics can be controlled in research, studies by Blanco-Penedo et al. [54] and Xu et al. [55] indicate that structural factors, such as herd size, barn type, and capital assets, may still differ. ORG farms are generally associated with lower economies of scale due to their reliance on pasture-based systems and regulatory constraints on chemical inputs [56,57], which contribute to lower productivity per animal and per acre [58]. In our case, the topographic challenges of mountain landscapes with steep meadows further complicate grazing, as noted by Holighaus et al. [31]. Additionally, Walsh et al. [59] suggest that smaller farms often transition to ORG practices due to economic struggles, seeing ORG milk production as a potential route to profitability, with fewer barriers to adoption. In contrast, larger farms tend to favor CON systems due to economies of scale [60]. Farmer-specific factors, such as attitudes or external incentives, were excluded from this analysis to maintain focus on broader, farm-level factors directly related to production practices and economic outcomes, although they may influence the profile of ORG dairy farms [61]. In addition, variability across studies complicates generalizations about whether ORG or CON systems are more advantageous, as farm characteristics can differ depending on sampling design and study objectives [14]. Therefore, although our study does not represent all forms of Alpine dairy farming, it provides a focused framework for assessing the environmental costs of ORG and CON systems by ensuring the comparability of counterfactual farms.

3.2. Input-output comparison of CON and ORG dairy farms

Table 3 compares feeding practices and production outcomes between CON and ORG dairy farms after propensity score matching. The labels “before” and “after” in the table indicate the means adjusted for confounding factors, while the columns titled ATT correspond to the analysis of post-intervention values. Significant differences were observed in total feed rations, with CON farms providing higher daily dry matter intake per cow (18.366 vs. 16.555 kg DM/cow/day). Feeding composition also varied, with ORG farms relying more on pasture

Table 3
Farming system effect in term of economic indicators, feeding, and workload: before and after matching samples.

Item	Mean				Difference ATT	S.E[a] ATT	*t*-test ATT
	Before		After				
	CON	ORG	CON	ORG			
Milk yield (kg ECM/cow/year)	**9505.33**	**6539.47**	9069.80	6796.70	−2273.10	798.63	−3.87[c]
Milk quality							
Fat (%)	4.015	3.944	3.939	4.046	0.107	0.229	0.73
Protein (%)	0.035	0.032	0.034	0.034	−0.001	0.002	−1.03
Total feed ration (kg DM/cow/day)	**18.109**	**16.365**	18.366	16.555	−1.811	1.028	−2.16[c]
Pasture (kg DM/cow/day)[b]	0	1.681	0	1.787	–	–	–
Hay (kg DM/cow/day)	**8.507**	**11.963**	8.347	12.000	3.653	2.894	1.68
Grass silage (kg DM/cow/day)[b]	3.745	0	3.612	0	–	–	–
Maize silage (kg DM/cow/day)[b]	1.248	0	1.583	0	–	–	–
Concentrate (kg DM/cow/day)	**4.613**	**2.724**	4.815	2.770	−2.045	0.715	−5.04[c]
Workload							
Per farm (h/farm/year)	**2001.417**	**1332.250**	1569.500	1231.875	−337.625	626.787	−0.93
Per cow (h/LU/year)	96.973	101.525	71.849	75.295	3.446	62.944	0.18

Bold indicates *t*-test significance at 5 % level.
[a] Bootstrapped standard error, 50 replications; ATT = Average Treatment Effect on the Treated.
[b] Not applicable due to farmer decisions or regulations.
[c] Significant at 5 % level.

(1.787 kg DM/cow/day), while CON farms used greater amounts of grass silage (3.612 kg DM/cow/day) and maize silage (1.583 kg DM/cow/day). Additionally, CON farms supplied more concentrate (4.815 vs. 2.770 kg DM/cow/day), reflecting distinct feeding strategies. These differences corresponded with higher milk yields in CON systems (9069.80 vs. 6796.70 kg ECM/cow/year), representing a 33.4 % productivity advantage. However, no significant differences were found in milk fat or protein content, and workload remained comparable, suggesting that productivity differences were primarily driven by feed intensity rather than labor input.

The feed ration and milk yield in our study are similar to those reported by Antony et al. [9], who conducted an environmental cost analysis in the Southern region of Germany, within the same Alpine region (Fig. 1). Our results also align with those of Orjales et al. [62], who observed that ORG farms generally have lower total dry matter intake compared to CON farms, with ORG farms relying more on pasture and hay. Specifically, both systems in our study follow a homegrown forage-based systems, emphasizing a higher intake of hay, with ORG farms using reduced concentrate (maximum 25 % of the annual feed) and no silage feeding, in accordance with EUR-Lex [37] regulations, as shown in Table 3. ORG farms produced less milk per cow than CON farms, which is consistent with numerous studies [15,63]. As noted by Bórawski et al. [64] and Manuelian et al. [65], the lower yield in ORG systems is primarily due to the reduced use of concentrate feeds and greater reliance on pasture, limiting the energy available for high milk production, even when breed and basic diet are controlled.

In contrast, CON farms produce more milk due to their higher use of concentrate feed, maize silage, and forage silage [9,62,66], as shown in our results (Table 3). Although the milk yield was lower, our study found comparable fat and protein content (Table 3), consistent with the findings of Manuelian et al. [65]. However, this does not align with the findings of Ormston et al. [67], who reported slightly higher fat and protein concentrations in CON farms. We argue that the higher hay intake in CON diets, combined with substantial silage and concentrate, contributes to similar fat and protein content (Table 3). Similarly, Battaglini et al. [68] found no significant differences in milk fat content between ORG and CON systems when hay was a major part of the diet. However, Bang et al. [69] raised an important question regarding whether farmers should operate their farms conventionally or organically, noting that the decision depends not only on input-output orientation but also on the farm's financial performance and its environmental impact.

3.3. Economic performances

Table 4 indicates that ORG dairy farms incur significantly higher operating costs per kg of ECM (0.486 €/kg ECM) compared to CON dairy farms (0.368 €/kg ECM). This difference is largely driven by higher costs for both home-grown feed (0.152 vs. 0.099 €/kg ECM) and purchased concentrate feed (0.212 vs. 0.154 €/kg ECM) in ORG farms. Although CON farms report higher fixed costs per farm annually (78,371 vs. 58,208 €/farm/year), no statistically differences were observed when these were expressed per kg ECM (0.461 vs. 0.647 €/kg ECM). ORG farms also faced higher herd renewal purchases (0.076 vs. 0.056 €/kg ECM) and insurance costs (0.098 vs. 0.029 €/kg ECM). Despite these higher operating costs, ORG farms benefit from higher revenue per kg ECM (1.021 vs. 0.744 €/kg ECM), driven by premium milk prices (0.811 vs. 0.597 €/kg ECM, $p < 0.05$) and greater subsidies (0.117 vs. 0.062 €/kg ECM), offsetting the increased production costs, even though total milk revenue per farm is lower (95,678 vs. 107,811 €/farm/year).

Although the difference is statistically insignificant, the total cost of production (CoP) for ORG farms was 0.305 €/kg ECM higher than for CON farms, driven by costs related to homegrown feed, purchased feed, herd renewal, and insurance (Table 4). Our study also reveals a higher CoP for ORG milk (1.13 €/kg ECM) and CON milk (0.83 €/kg ECM) compared to the German Alpine region (0.32 vs. 0.50 €/kg ECM for CON and ORG, respectively) [9] and the national average of 0.92 €/kg ECM across Germany [70]. It is clear that larger economic scales result in higher costs per farm, which are offset by increased milk production that lowers the cost per unit of product. Indeed, differences in CoP methods may introduce bias in comparisons across studies. The higher CoP in ORG farming is linked to higher feed costs, as organic hay and concentrates are more expensive and less efficient than conventional feed [71]. In our case, mountain dairy farmers are of high importance for the conservation of grassland, as farmers use, on average, more than 10 ha for hay production and pasturing [2]. However, the lower use of concentrate feed (Table 3) and the lower quality of hay produced [49], result in lower milk yields and increased feed costs per unit of output. In contrast, the cultivated area for silage maize in South Tyrol is relatively small (approximately 1200 ha), with growth constrained by mountainous climatic conditions (short growing seasons and limited heat) and a lack of arable land in hilly regions [72]. Compared to hay-based feed rations, mixed feed with maize silage is more cost-effective due to its higher yield per hectare and better feed conversion [73]. In addition, ORG farming incurs higher costs for specialized harvesting techniques, with these challenges further exacerbated by climatic variability [74]. However, Bang et al. [69] made an exception, stating that if high-quality

Table 4
Economic performance of CON and ORG alpine dairy farms (all data for the reference year 2022, in €2022): before and after matching samples.

Items	Mean				Difference ATT	S.E[a] ATT	*t*-test ATT
	Before		After				
	CON	ORG	CON	ORG			
Costs							
Operating costs (€/farm/year)	63.456	52,246	69,262	56,482	−12,779	21,516	−0.75
Operating costs (€/kg ECM/year)	**0.390**	**0.513**	0.368	0.486	0.118	0.081	3.11[c]
Home grown feed	**0.123**	**0.166**	0.099	0.152	0.053	0.030	2.96[c]
Purchased feed (concentrate)	**0.149**	**0.203**	0.154	0.212	0.058	0.040	2.45[c]
Veterinary cost	0.008	0.011	0.008	0.012	0.003	0.005	0.80
Artificial insemination	0.008	0.011	0.009	0.012	0.003	0.005	0.80
Dairy related expenses	0.027	0.017	0.018	0.014	−0.004	0.046	−0.58
Energy (fuel, electricity)	**0.044**	**0.061**	0.042	0.055	0.012	0.018	1.02
Machinery and building upkeep	0.031	0.045	0.039	0.032	−0.007	0.023	−0.44
Fixed costs (€/farm/year)	73,413	59,606	78,371	58,208	−20,162	12,727	−2.18[c]
Fixed costs (€/kg ECM/year)	0.462	0.876	0.461	0.647	0.186	0.271	1.04
Depreciation	**0.138**	**0.234**	0.181	0.220	0.039	0.068	0.48
Building	**0.058**	**0.133**	0.099	0.107	0.008	0.063	0.16
Machinery	0.080	0.101	0.082	0.113	0.031	0.028	0.65
Herd renewal purchases	**0.053**	**0.080**	0.056	0.076	0.020	0.006	4.02[c]
Insurance	**0.043**	**0.102**	0.029	0.098	0.069	0.028	1.89[b]
Fees and consulting	0.010	0.018	0.007	0.016	0.009	0.009	1.35
Other cost	**0.015**	**0.062**	0.038	0.030	−0.008	0.023	−0.42
Opportunity cost of family labour	0.202	0.381	0.150	0.207	0.057	0.199	0.99
Total cost (€/farm/year)	**136,870**	**111,852**	147,632	114,691	−32,941	29,940	−1.34
Total cost (€/kg ECM/year)	**0.852**	**1.389**	0.829	1.133	0.305	0.308	1.53
Revenue							
Total milk revenue (€/farm/year)	98,991	86,379	107,8111	95,678	−12,134	29,740	−0.57
Total revenue (€/kg ECM/year)	**0.734**	**1.006**	0.744	1.021	0.277	0.047	5.95[c]
Milk price	**0.601**	**0.776**	0.597	0.811	0.214	0.333	8.94[c]
Cattle sales	**0.074**	**0.096**	0.085	0.093	0.008	0.027	0.37
Subsidies	**0.059**	**0.134**	0.062	0.117	0.055	0.035	2.64[c]
Returns (€/kg ECM/year)							
Level 1 (TC - milk price)	−0.250	−0.613	−0.232	−0.322	−0.091	0.305	−0.45
Level 2 (TC - (milk price + cattle sales)	−0.176	−0.517	−0.146	−0.229	−0.083	0.300	−0.43
Level 3 (TC - milk price + cattle sales + subsidies)	−0.118	−0.383	−0.085	−0.112	−0.028	0.297	−0.16
Level 4 (OC - milk price)	0.211	0.263	0.229	0.325	0.049	0.089	1.96[b]
Level 5 (OC - milk price + cattle sales + subsidies)	**0.344**	**0.493**	0.376	0.535	0.159	0.114	2.83[c]

Bold indicates *t*-test significance at 10 % level.
[a] Bootstrapped standard error, 50 replications; ATT = Average Treatment Effect on the Treated.
[b] Significant at 10 % level.
[c] Significant at 5 % level.

forage is readily available and livestock expansion is constrained by animal housing and milk quota restrictions, ORG farming may outcompete CON farming.

Economic returns analysis revealed negative returns at Level 1 (total costs and milk prices) for both systems, with no significant differences (Table 4). This negative profitability persisted even when cattle sales and subsidies were included (Levels 2 and 3). When fixed costs were excluded (Levels 4 and 5), particularly the opportunity cost of family labor (30 % of the total fixed costs), which represents the income the family could have earned if their labor had been employed outside the farm, both systems showed positive returns. ORG farms, however, demonstrated significantly higher returns (0.325 vs. 0.229 €/kg ECM at Level 4; and 0.535 vs. 0.376 €/kg ECM at Level 5). This suggests that while organic systems face higher production costs per unit of output, premium milk prices and subsidies help offset these expenses, contributing to better short-term economic performance. However, excluding fixed costs highlights that long-term viability remains uncertain as fixed costs are essential for sustaining operations. Crowder and Reganold [75] reviewed 129 studies comparing organic and conventional farming, finding that organic farms were 22–35 % more profitable due to the price premium. Specifically, dairy farms in the Farm Accountancy Data Network (FADN) show that ORG farms generate higher revenue per liter of milk, lower production costs [7,26], and higher gross margins per cow [76]. However, Lambotte et al. [14], using propensity score weighting, found that after controlling for self-selection, gross margins are not significantly different between ORG and CON dairy farms, which supports our conclusion (Table 4) that, although less productive, ORG farms have a similar economic performance to CON farms. To conclude, both CON and ORG farms in this study can be considered economically viable according to Vrolijk et al. [77]. Although the economic profit is negative (Levels 1–3; Table 4), the positive cash flow (Levels 4 and 5; Table 4) indicates that, despite the losses, farmers can sustain short-term operations. This suggests that ORG systems, through premium prices and subsidies, can achieve competitive returns, thereby clarifying the economic viability of transitioning to organic farming under the given circumstances.

3.4. Environmental impact asessment

Both systems showed no significant differences in GWP_{100} and AP per kilogram of ECM (Table 5). However, ORG dairy farms exhibited significantly lower MEP (−0.0007 kg N-eq kg^{-1} ECM) and TE (−0.1573

Table 5
Farming system effect (conventional and organic) on environmental impact in the alpine dairy farms, data per kg ECM milk and m2 grassland: before and after matching samples.

Impact category	Mean				Difference ATT	S.E[a] ATT	*t*-test ATT
	Before		After				
	CON	ORG	CON	ORG			
GWP_{100} (kg CO_2-eq kg^{-1} ECM)	**1.1436**	**1.3080**	1.1736	1.2618	0.0881	0.138	0.95
AP (kg SO_2-eq kg^{-1} ECM)	0.0045	0.0058	0.0049	0.0056	0.0006	0.001	0.67
MEP (kg N-eq kg^{-1} ECM)	**0.0017**	**0.0009**	0.0016	0.0009	−0.0007	0.001	−2.29[b]
TE (kg 1,4-DCB kg^{-1} ECM)	**0.9504**	**0.3704**	0.9913	0.3769	−0.1573	0.238	−3.91[b]
LU (m^2 crop-eq yr kg^{-1} ECM)	**0.9495**	**1.5446**	0.9658	1.5136	0.5479	0.172	2.97[b]
WC (m^3 kg^{-1} ECM)	0.0168	0.0168	0.0201	0.0176	−0.0024	0.006	−0.56
GWP_{100} (kg CO_2-eq kg^{-1} m^{-2})	1.2366	0.9874	1.7489	0.9671	−0.7818	0.587	−4.12[b]
AP (kg SO_2-eq kg^{-1} m^{-2})	0.0047	0.0041	0.0072	0.0039	−0.0032	0.002	−2.75[b]
MEP (kg N-eq kg^{-1} m^{-2})	**0.0017**	**0.0007**	0.0024	0.0007	−0.0018	0.001	−3.35[b]
TE (kg 1,4-DCB m^{-2})	**1.0069**	**0.2769**	1.4854	0.2826	−1.2028	0.622	−4.49[b]
WC (m^3 yr kg^{-1} m^{-2})	0.0198	0.0128	0.0299	0.0133	−0.0165	0.015	−2.57[b]

GWP100 = global warming potential in 100-year horizon; AP = acidification potential; MEP = marine eutrophication potential; TE = terrestrial ecotoxicity; LU = land use; WC = water consumption; CO2-eq = carbon dioxide equivalents; SO2-eq = sulfur dioxide equivalents; N-eq = nitrogen equivalents; 1,4-DCB = 1,4-dichlorobenzene; ECM = energy-corrected milk; ATT = Average Treatment Effect on the Treated.
Bold indicates *t*-test significance at 5 % level.
[a] Bootstrapped standard error, 50 replications.
[b] Significant at 5 % level.

kg 1,4-DCB kg^{-1} ECM), while requiring significantly more LU (0.5479 m^2 crop-eq yr kg^{-1} ECM) compared to their counterfactual farms. When impacts were assessed per square meter of grassland, ORG systems consistently demonstrated significantly lower environmental impacts across all categories, including GWP_{100} (−0.7818 kg CO_2-eq kg^{-1} m^{-2}), AP (−0.0032 kg SO_2-eq kg^{-1} m^{-2}), MEP (−0.0018 kg N-eq kg^{-1} m^{-2}), TE (−1.2028 kg 1,4-DCB m^{-2}), and water consumption (WC) (−0.0165 m^3 yr kg^{-1} m^{-2}), relative to CON farms (Table 4). These findings highlight the ecological strength of organic systems under land-based functional assessment [78].

We focus on discussing GWP_{100} separately, as carbon emissions often receive more public and policy attention than other environmental impacts [79,80]. Despite potential differences in the LCA models, the GWP_{100} values observed in this study (Table 5) were slightly higher than those reported by Antony et al. [9], which ranged from 0.93 to 1.12 kg CO2-eq per 1 kg of ECM. Performing no allocation, GWP_{100} emissions did not significantly differ between the groups per kg of ECM but were significantly lower per agricultural area for ORG farms (Table 5), which aligns with similar findings by Pirlo and Lolli [15]. The finding may be explained by the lower milk yields per cow and the larger agricultural area as well as lower stocking rate per farm on ORG farms compared to CON farms (Table 3). Numerous studies have shown that while ORG dairy farms typically use fewer synthetic fertilizers and pesticides, they also have higher enteric methane emissions, a greater proportion of emissions from manure, and lower emissions from concentrate feed production, though these factors are often offset by lower productivity per cow [81–84]. Consequently, greenhouse gas emissions per cow are spread over less milk, leading to a higher GWP_{100} per kg of ECM [15]. In contrast, under favorable management conditions and when soil organic carbon is considered, some studies report that organic and grassland-based dairy systems achieve lower greenhouse gas emissions and a reduced net carbon footprint per unit of land, due to lower input use and stocking densities [15,85,86]. In addition, as previously mentioned, both farming systems in this study employed similar feed management (homegrown forage-based systems), with the exception of the use of silage and pasture (Table 3), which may result in indifferent emissions per unit of product. Waghorn and Hegarty [87] emphasized that one key factor influencing efficiency and carbon emissions is the amount of feed (forage plus concentrates) each cow requires to produce 1 L of milk. Liang et al. [88] also explained that under certain conditions, small variations in feed management have a relatively minor effect on emissions per metric tonne of ECM.

The non-significant AP values per kilogram of ECM (Table 5) are primarily due to the absence of synthetic fertilizer use, as fewer South Tyrolean farms purchased or applied such inputs, mostly related to local premiums which are paid to farms when solely organic fertilizers (slurry, manure) are used [89]. ORG farms consistently use more land per kg of ECM than CON farms (Table 5), which aligns with previous studies showing that greater reliance on pasture and hay, along with lower milk yield, requires more land [15,90]. In addition, mountain areas, particularly at higher altitudes, have low or no suitability for arable crops, and the steep slopes further increase land use requirements [91]. Despite this, ORG farms show significantly lower environmental impacts per unit of agricultural land, and lower MEP and TE per kg of ECM, in line with previous research [4,15,86]. These benefits stem from more ecological management practices [4], supporting Lambotte's [14] view that ORG farms can offer strong economic performance without compromising mitigation potential. The relevance of CON and ORG dairy systems aligns with similar conclusions drawn by Zanon et al. [43] in both low and high-input Alpine dairy farm contexts. High-input systems tend to have lower GWP_{100} (per kg of ECM) but show no significant difference in AP between systems, with higher MEP and significant LU variability, which depends on seasonality. However, the debate over the environmental impact of CON versus ORG systems remains unresolved due to factors such as functional units, analysis methods, farm intensity, feed management, and regional differences [15]. Irrespective of these context-dependent factors, more ecological farming practices reduced environmental damage, leading to lower restoration and prevention costs [14], as further detailed in Annex 2 and 3.

3.5. Environmental cost of alpine dairy milk

The reference costs and sensitivity analysis of environmental costs across various dairy farming systems is summarized in Annex 3 and Table 6. The results indicate that CON demonstrated lower values across nearly all environmental impact categories. Specifically, for GWP_{100}, CON in the CE Delft: EU27 reference recorded €0.205 per kg ECM (52 %), while ORG was slightly higher at €0.220 per kg ECM (50 %). Similar trends were observed in the CE Delft: Italy and True Price references, where ORG consistently displayed higher GWP_{100} costs. Under the True Price model, GWP_{100} cost for CON was €0.188 per kg ECM (37 %), while ORG's cost was €0.202 per kg ECM (31 %). In absolute terms, the production of 1 kg of ECM milk causes climate costs within a range of around 20 € cents.

Table 6
Sensitivity analysis of environmental costs of the different dairy farming systems and reference cost, in €$_{2022}$ per kg ECM: mean after matching samples.

Items	CE Delft: EU27				CE Delft: Italy				True Price: EU27			
	CON		ORG		CON		ORG		CON		ORG	
Economic cost (€/kg^{-1} ECM)	0.829		1.133		0.829		1.133		0.829		1.133	
Environmental cost (€/kg^{-1} ECM)	0.397	(100)	0.437	(100)	0.371	(100)	0.425	(100)	0.503	(100)	0.643	(100)
GWP_{100} (€/kg CO_2-eq kg^{-1} ECM)	0.205	(52)	0.220	(50)	0.179	(48)	0.192	(45)	0.188	(37)	0.202	(31)
AP (€/kg SO_2-eq kg^{-1} ECM)	0.049	(12)	0.055	(13)	0.049	(13)	0.056	(13)	0.024	(5)	0.026	(4)
MEP (€/kg N-eq kg^{-1} ECM)	0.049	(12)	0.027	(6)	0.043	(12)	0.024	(6)	0.023	(5)	0.013	(2)
TE (€/kg 1,4-DCB kg^{-1} ECM)	0.00091	(0.2)	0.00034	(0.1)	0.00114	(0.3)	0.00044	(0.1)	0.00030	(0.1)	0.00011	(0.0)
LU (€/m^2 crop-eq yr kg^{-1} ECM)	0.075	(19)	0.117	(27)	0.096	(26)	0.150	(35)	0.242	(48)	0.378	(59)
WC (€/m^3 kg^{-1} ECM)	0.018	(5)	0.016	(5)	0.004	(1)	0.003	(1)	0.027	(5)	0.023	(4)
Total economic and environmental cost of mountain dairy milk	1.226		1.571		1.197		1.557		1.331		1.775	

Proportional contribution of each impact assesment (%) in paranthesis.

Other environmental impacts, including AP, MEP, and TE, similarly reflected the environmental cost advantage of CON. In the CE Delft: EU27 reference, AP for CON was €0.049 per kg ECM, contributing 12 % to the total environmental cost, while ORG recorded a higher AP of €0.055 per kg ECM, representing 13 % of the overall environmental cost. In terms of MEP, CON registered €0.049 per kg ECM (12 %), while ORG exhibited a lower value of €0.027 per kg ECM (6 %). For TE, CON incurred €0.00091 per kg ECM (0.2 %), in contrast to ORG's €0.00034 per kg ECM (0.1 %), further highlighting the lower environmental impact of CON.

LU was higher in ORG across all references. In the CE Delft: EU27 reference, LU for CON was €0.075 per kg ECM (19 %), while ORG showed a higher LU of €0.117 per kg ECM (27 %). In terms of WC, CON displayed a slightly higher environmental cost (€0.018 per kg ECM, 5 %) compared to ORG (€0.016 per kg ECM, 5 %) in the same reference. Similarly, under the True Price model, water consumption was a more prominent factor, contributing 5 % for CON and 4 % for ORG. The total economic and environmental cost of alpine dairy milk ranged from €1.197 to €1.331 per kg ECM for CON and €1.557 to €1.775 per kg ECM for ORG across the different reference rates. ORG exhibited higher costs than CON, with the greatest disparity observed in the True Price reference, where the costs were €1.775 per kg ECM for ORG, compared to €1.331 per kg ECM for CON.

Monetizing environmental impacts enables the aggregation of various impact categories and the evaluation of their relative contributions to total costs. In this study, ORG farm milk exhibits higher environmental costs than CON farm milk (Table 6), which contrasts with earlier findings suggesting that ORG systems have comparable or lower environmental impacts for some categories (Table 4). This contradiction may be explained by the lower productivity of many ORG farms in our study, leading to higher costs per unit of milk, as well as variations in the monetary valuation of specific impact categories, particularly GWP100 and LU costs (Table 6). Although ORG systems may show lower impacts in certain indicators, the cumulative cost per kilogram of ECM can still be higher due to the greater valuation of specific categories. Overall, environmental costs account for nearly half of the economic production cost, with CON milk being approximately 10 % lower than ORG milk (Table 6). Among all categories, GWP_{100} contributes the most, representing approximately 30–50 % of total environmental costs, followed by LU at 20–60 %, while TE contributes the least, at less than 1 % (Table 6). These results are consistent with Antony et al. [9], although other studies, such as Chen and Holden [92] and Michalke et al. [11], report higher environmental costs, sometimes exceeding economic costs, with economic costs at €0.35 and €0.48/kg ECM and total environmental costs at €0.75 and €0.85/kg ECM for CON and ORG milk, respectively. Environmental cost uncertainties suggest that these costs might be influenced by methodological choices, including impact categories, cost rates, region, and study period.

Despite these findings, significant methodological uncertainties remain, particularly in the monetization of less tangible impacts such as ecotoxicity and land use [9]. These uncertainties suggest that the reported values may represent conservative estimates of actual environmental costs. Some impact categories may be underrepresented, potentially leading to an underestimation of the differences between ORG and CON production systems. Degieter's [22] systematic review of 92 life cycle costing studies highlights the persistent lack of consensus on cost definitions and system boundaries, complicating the comparability of findings across studies. Michalke et al. [11] stated that the uncertainty has two key implications. First, a robust assessment requires clear identification of the relevant impact indicators and the conditions underpinning the system being analyzed. Second, monetization methods at the midpoint level vary substantially and require further methodological refinement. For instance, this study did not include indicators such as freshwater and human toxicity, which were considered by Antony et al. [9]. Moreover, changing the pricing reference in this study could shift environmental cost estimates by up to €0.15 for CON and €0.20 for ORG milk per kg ECM (Table 6).

The meta-analysis of life cycle assessments of 742 agricultural systems by Clark and Tilman [93] highlighted that the key to sustainable food production lies in balancing the trade-offs between chemical input use and yield, achieved by increasing agricultural input efficiency, which is consistently associated with lower environmental impacts. However, the responsibility for sustainable production does not rest solely with producers, as farmers are more likely to adopt sustainable practices when there is clear market demand and consumer willingness to pay a premium for such products [94]. In the Alpine region context, the demand for organic milk remains relatively low due to several factors: higher prices compared to conventional milk, limited production capacity on small traditional farms, and the perception that organic milk is not inherently superior to conventional milk [95]. Consequently, transitioning fully to ORG farms may not be the most advisable recommendation at this time. However, expanding ORG farming with optimized input-output efficiency remains a viable strategy, particularly in mountain dairy farms, where small economic scales may present a low barrier to shifting from CON to ORG farms.

From a policy perspective, the current market system fails to internalize environmental costs, allowing natural resources to be exploited without accounting for the associated ecological burden [11]. This leads to inefficient resource use and negatively affects overall social welfare [96]. To address this issue, Laurent et al. [79] suggest incorporating a wider range of environmental indicators in sustainability assessments. Although more comprehensive pricing structures may appear economically unfeasible in certain scenarios [97], prioritizing the carbon footprint as the most widely used and bigger contribution (Table 6) could provide a pragmatic starting point for integrating environmental costs into agricultural policy. Still, Michalke et al. [11] argues against this approach, as TCA studies cannot assess the likelihood of these prices being implemented in practice, particularly given that consumer understanding and acceptance remain limited [98] as well as the uncertainty in accurately accounting for environmental impacts across diverse farming practices, regions, and methods [9]. Therefore, prior fully or partially internalizing environmental costs, enhancing farm productivity and efficiency could yield greater economic and environmental benefits compared to switching from CON to ORG farms, thereby facilitating the transition to a sustainable dairy system.

3.6. Limitations

This study has several limitations that should be considered when interpreting the results. The sample size of 30 dairy farms limits the generalizability of the findings. While GWP and carbon emissions are well-regulated and extensively studied, this study highlights a gap in the assessment of LU cost rates. The use of the Netherlands' environmental cost rate may lead to an overestimation of LU costs, as the study region may experience lower biodiversity loss compared to the Netherlands. The study did not account for potential changes in milk production, such as the transition from conventional to organic farming, which typically requires more land due to lower yields per hectare. It should be noted at this point that no standardization or weighting of the various environmental impacts is undertaken for this study. From a statistical perspective, the application of PSM may not provide a completely fair counterfactual comparison between CON and ORG farms in this dataset. It is important to clarify the distinction between observed average differences and statistically significant differences in Section 3.3. While we note the observed differences, statistical significance helps determine whether these differences are likely to be meaningful or simply due to random variation. Future research should incorporate animal welfare costs, as the true cost in this study is based on an LCA, which excludes this factor. At this stage, estimating the environmental cost rate for the specific region, rather than using the average EU or Netherlands rate, would provide a valuable direction for further investigation. Additionally, a more detailed assessment of biodiversity aspects through individual farm studies appears to be a more promising direction for future research.

4. Conclusions

We apply a doubly robust estimator of the Average Treatment Effect on the Treated (ATT) through Propensity Score Matching (PSM) to evaluate the environmental impact and economic performance of organic (ORG) and conventional (CON) mountain dairy farms. This study demonstrates that ORG milk incurs higher total production costs per kg ECM compared to CON farms, primarily due to expenses related to homegrown and purchased feed, herd renewal, and insurance. While no statistically differences were found in fixed costs per kg of ECM, the operating costs of ORG farms were considerably higher, driven by the milk-to-feed price ratio. This suggests potential for improving herd size on ORG farms to enhance economies of scale, despite the challenges posed by mountain landscapes for forage production. ORG farms exhibit similar returns to CON farms, with higher returns due to premium milk prices and subsidies when fixed costs are excluded. This study also shows that dairy farms in South Tyrol produce more costly milk compared to other regions, relying on subsidies and higher milk prices to sustain operations. In addition, ORG farms demonstrate significantly lower impacts across all indicators per unit of agricultural land, while GWP_{100} and acidification potential (AP) remain similar to CON farms per kg of ECM. Although ORG farms in mountain regions perform better in terms of environmental impacts, they incur higher environmental costs per kg of ECM than CON farms. Environmentally speaking, internalizing comprehensive environmental costs into the milk price could promote efficient resource use and enhance overall social welfare. However, integrating these costs may be economically unfeasible due to limited consumer understanding and acceptance, though the increasing demand for ORG products. Nonetheless, before considering full or partial environmental cost internalization, expanding ORG farming remains a viable strategy to advance the transition to a sustainable dairy system, in alignment with the European Union's Farm to Fork strategy. Although this study has certain limitations in terms of methodology and data, this approach offers a valuable means of understanding the hidden environmental costs of dairy products and can serve as a tool to inform policy decisions and raise awareness in the agricultural sector.

CRediT authorship contribution statement

Agung Triatmojo: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation. **Greta Fichter:** Methodology, Investigation, Formal analysis, Data curation. **Christian Fischer:** Writing – review & editing, Supervision. **Matthias Gauly:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Thomas Zanon:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Ethical statement

The experimental and notification procedures were carried out in compliance with Directive 86/609/EEC.

Fund

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Declaration of competing interest

The authors affirm that they possess no identifiable conflicting financial involvements or personal affiliations that might have seemed to impact the research presented in this manuscript.

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Annex 1: Emission factors and equations utilized to estimate the environmental emissions of each pollutant. Modified from Sabia et al. [99]

Environmental pollutant	Source	Equations	Emission Factor	Reference
kg CO_2-eq	Diesel use	CO2-eq. = 1 diesel * EF	3.14	Romano et al. [48]
	Electricity use	CO2-eq. = kWh * EF	0.40	Romano et al. [48]
kg CH_4	Enteric	CH_4 = kg DMI herd^{-1} * 18.45 (Gross Energy MJ kg^{-1} DMI) * Ym/55.65	Ym = 4 %; 6.5 %	IPCC [47]; Opio et al. [100]
	Storage and Pasture	CH_4 = VS * B_0 * 0.67 * MCF/100 * MS	MCF pit storage = 27 MCF pasture = 1.5 Ms pit storage = 20 % MS pasture = 5 %	IPCC [47]
kg NH_3	Storage	Nvolatilization = Nex (conf. syst.) * MS * Frac_GasMS/100 * 17/14	Frac_GasMS solid storage: 40	IPCC [101]
kg N_2O direct	Storage	N_2O = Nex (conf. syst.) * MS * EF * 44/28	0.02	Romano et al. [48]
	Pasture	N_2O = Nex (pasture) * MS * EF * 44/28	0.007	IPCC [47]
kg N_2O indirect	Storage	$N_2O_{(G)}$ = Nvolatilization * EF * 44/28	0.01	IPCC [47]
	Field/Pasture	$N_2O_{(ATDN)}$ = [(Nsn * Frac_GasF) + ((Non + Nprp) * Frac_GrasM)] * EF * 44/28	0.01	IPCC [101]
		$N_2O_{(L)}$ = (Nsn + Non + Ncr + Nsom + Nprp) * Frac_Leach * EF *44/28	0.0075	IPCC [101]

Ym = methane conversion factor; DMI = Dry matter intake; MCF = Methane conversion factor; MS = Manure management system usage; VS = volatile solids (3.9 kg/hd/day); B_0 = maximum methane producing capacity (0.1 m^3 CH_4/kg VS); Nex = annual N excretion for livestock category; Nsn = annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1}; Non = annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils, kg N yr^{-1}; Ncr = annual amount of N in crop residues, including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N yr^{-1}; Nsom = annual amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg N yr^{-1}; Nprp = annual amount of urine and dung N deposited by grazing animals on pasture, range, and paddock, kg N yr^{-1}; DE = Digestible Energy.

Annex 2: Definition of the environmental cost for each impact category in current scientific literature. Modified from CE Delft [20] and True Price Foundation [21]

Items	Unit	Sources	Explanation
GWP_{100}	€/kg CO_2-eq	CE Delft	The economic damages associated with the impacts of climate change, particularly those resulting from greenhouse gas (GHG) emissions. The primary metric used to quantify these costs is the Social Cost of Carbon (SCC), which estimates the monetary value of the damage caused by emitting one additional tonne of CO2. This includes various negative effects such as increased health risks, damage to infrastructure, and losses in agricultural productivity, among others.
		True Price	A restoration cost which expresses the abatement cost[1] for achieving the policy targets of reducing greenhouse gas emissions to meet the two-degree target as set in the Paris Agreement, based on a meta-study of 62 marginal abatement cost estimates.
AP	€/kg SO_2-eq	CE Delft	The environmental damage caused by acidifying emissions, which affect biodiversity through changes in soil conditions, as well as the damage to buildings (clean-up and restoration costs) not covered by particulate matter formation. These costs have been adjusted based on studies from the European Environment Agency, the Network of European Environmental Departments 2008 Project, and the ReCiPe 2016 endpoint valuation.
		True Price	Compensation cost reflects the social cost of pollution and the economic welfare loss from ecosystem damage. This damage is valued based on the loss of ecosystem services, as explained for ecotoxicity. Recipe 2016 midpoint-to-endpoint conversion factors for acidification are used to derive monetization factors. At the midpoint level, the indicator uses global monetization, though country-specific conversion factors for gases (NH3, SOx, NOx) can be applied.
MEP	€/kg N-eq	CE Delft	The environmental damage caused by nitrogen discharges into seawater, which leads to the degradation of marine ecosystems. These costs are estimated through various sources, including the Dutch levy on nitrogen discharges, academic studies using preference methods, and the European average valuation of nitrogen emissions to saltwater. These estimates are based on inflation adjustments, scarcity of natural capital, and the effects of nitrogen discharges on coastal regions.
		True Price	A combination of restoration and compensation costs based on a literature review on the costs of eutrophication. Restoration costs express average abatement cost for bringing nutrient levels to a regulatory target, for the impacts that are reversible. Compensation costs express other damage (economic damage, damage to human health and biodiversity loss), for residual impacts after restoration has taken place.
TE	€/kg 1,4-DCB	CE Delft	The environmental damage caused by toxic substances, such as 1.4-dichlorobenzene, discharged into terrestrial ecosystems. The valuation is based on characterization factors from ReCiPe, which express ecotoxicity in terms of the relative toxicity of this substance to aquatic organisms.
		True Price	The compensation cost represents the social cost of pollution, reflecting the economic loss caused by ecosystem damage. This damage is valued based on the loss of ecosystem services, using the annual value of services per hectare from a study of six biomes. Monetization factors are derived using Recipe 2016 midpoint conversion factors for ecotoxicity.
LU	€/m^2 crop-eq year	CE Delft	The environmental impact of land use change, particularly in terms of biodiversity loss. The valuation is based on the SCBA Nature Working Guide and incorporates species richness valuation, adjusted over 50 years with a 2.25 % discount rate. The updated approach assumes a 50-year land use period and factors in biodiversity loss annually, with recovery occurring after 50 years, as outlined in ReCiPe 2016.
		True Price	A compensation cost which expresses the opportunity cost of land occupation based on the value of ecosystem services for main biomes based on a meta-analysis from The Economics of Ecosystems and Biodiversity.
WC	€/m^3 year	CE Delft	The environmental impact of water depletion, affecting the availability of water for humans, animals, and ecosystems. Water scarcity can result in health issues, loss of grazing land, biodiversity loss, and declines in fish species due to reduced river discharge. Water scarcity is valued by assessing its impacts on ecosystem services and human health, using characterization factors from ReCiPe 2016. The valuation includes effects on human health (malnutrition), terrestrial ecosystems (decline in Net Primary Productivity), and freshwater ecosystems (loss of fish species), with impacts determined through midpoint to endpoint conversion factors.
		True Price	A restoration cost which expresses the annualized cost of desalination, including the cost of operation and maintenance, electrical and thermal energy, as well as the cost of covering and repaying initial capital and operational costs of desalination.

Annex 3: Overview of cost rates in the current scientific literature (all data for the reference year 2022, in €$_{2022}$); bold = value used

Items	Unit	Sources	Country	Environmental rate/unit		
				Low	Central	High
GWP_{100}	€/kg CO_2-eq	CE Delft	EU27	0.055	0.142	**0.175**
			Netherland	0.056	0.145	0.179
			Italy	0.048	0.124	**0.152**
		True Price	EU27			**0.16**
AP	€/kg SO_2-eq	CE Delft	EU27	2.904	5.754	**10.155**
			Netherland	3.773	7.212	11.968
			Italy	3.215	6.144	**10.196**
		True Price	EU27			**4.82**
MEP	€/kg N-eq	CE Delft	EU27	8.342	15.560	**30.136**
			Netherland	8.529	15.908	30.812
			Italy	7.266	13.553	**26.250**
		True Price	EU27			**14.50**
TE	€/kg 1,4-DCB	CE Delft	EU27	0.00049	0.00070	**0.00091**
			Netherland	0.00075	0.00106	0.00137
			Italy	0.00064	0.00090	**0.00117**
		True Price	EU27			**0.00030**
LU	€/m^2 crop-eq year	CE Delft	EU27	0.041	0.059	**0.078**
			Netherland	0.064	0.090	0.116
			Italy	0.054	0.077	**0.099**
		True Price	EU27			**0.250**
WC	€/m^3 year	CE Delft	EU27	0.000	0.444	**0.886**
			Netherland	0.000	0.153	0.202
			Italy	0.000	0.130	**0.172**
		True Price	EU27			**1.330**

Data availability

Data will be made available on request.

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