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Environmental footprint of dehydrated alfalfa forage production in Italy: A life cycle assessment with additional information on environmental benefits

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A R T I C L E I N F O

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A B S T R A C T

Dehydrated alfalfa forage is a key feed resource in Mediterranean agriculture, serving downstream sectors such as livestock production. However, its processing relies on energy-intensive drying techniques, which involve potential environmental impacts. This study presents a Life Cycle Assessment (LCA) of dehydrated alfalfa production in Italy, conducted in accordance with ISO 14040 and ISO 14044 standards and the applicable Product Category Rules (PCR). The objective is to quantify the cradle-to-gate environmental impacts per tonne of baled dehydrated alfalfa and to assess the potential environmental co-benefits associated with alfalfa cultivation. Primary data were collected from five Italian forage processors over a five-year period (2019–2023), representing a cumulative dataset equivalent to 25 production years and allowing both inter-annual variability and variability among facilities to be considered. The results, assessed using the Environmental Footprint (EF) 3.1 midpoint method, show that the production of one tonne of dehydrated alfalfa emits, on average, 243 $kgCO_2eq$, with the dehydration phase accounting for nearly half of total greenhouse gas emissions. Energy consumption averages approximately 360 kWh per tonne. The variability analysis shows that cultivation-related flows are affected by both temporal and company-specific factors, whereas energy consumption in the dehydration stage is driven by differences among facilities. Despite its energy-demanding process, alfalfa cultivation offers potential environmental co-benefits, including improved soil structure and biological nitrogen fixation. However, nitrogen fixation does not lead to substantial emission reductions due to limited fertilizer savings in subsequent crop rotations. Carbon uptake in root and harvested biomass is reported in addition to LCIA results.

1. Introduction

1.1. Background

Agriculture in the European Union (EU) is faced with the dual challenge of responding to rising demand for food and feed while reducing its environmental impact. The sector remains a major source of greenhouse gas (GHG) emissions, contributing around 450–500 Mt CO_2 equivalent per year, about 13.1% of total EU-27 emissions in 2021 (European Environment Agency, 2021). Despite a slow downward trend over the long term, agriculture continues to be a focus of policies aimed at promoting more sustainable practices (European Court of Auditor, 2024). Through the Farm to Fork strategy and the Common Agricultural Policy (CAP), the EU promotes climate-neutral and environmentally sustainable agriculture by supporting practices such as crop rotation, cover cropping, and the use of legumes to foster soil health and biodiversity (European Commission, 2025). In this context, alfalfa (*Medicago sativa* L.), a perennial forage legume also known as lucerne, could play an important role in European agriculture. Alfalfa cultivation is traditionally valued for its high-protein forage (8–10% for the first cut and 18–20% for the subsequent cuts) and as a rotational crop that improves soil fertility (Bucciarelli et al., 2021; Song et al., 2021). As a deep-rooted legume, alfalfa can fix atmospheric nitrogen in symbiosis with soil bacteria, reducing the need for synthetic nitrogen fertilizers in crop rotations. Its extensive root system also enhances soil structure, prevents erosion, and increases soil organic matter and water retention capacity (Koudahe et al., 2022). The environmental co-benefits of alfalfa, including enhanced soil fertility, nitrogen fixation, and

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biodiversity support, have led to its inclusion in European agri-environmental schemes intended to mitigate the impacts of intensive agriculture and strengthen agro-ecosystem resilience (González del Portillo et al., 2022). Despite these benefits on the cultivation side, dehydrated alfalfa forage production involves energy-intensive industrial processes. In Italy, as in several other European countries (notably France and Spain), a significant portion of alfalfa is artificially dehydrated shortly after harvest to produce a stable, high-quality feed product, usually in the form of dried bales or pellets (Bernadette Julier et al., 2017). This dehydration process, essentially controlled drying of green alfalfa using large rotary or belt dryers fueled often by natural gas, enables the preservation of nutritional quality and year-round storage, supporting the dairy and livestock industries feed supply. However, the drying operation consumes considerable energy and results in GHG (Greenhouse Gases) emissions and other environmental impacts. With increasing focus on the sustainability of feed production, it is crucial to quantify the environmental footprint of dehydrated forage and identify improvement opportunities.

1.2. Data variability and research gap

Life Cycle Assessment (LCA) is a standardized methodological framework well-suited to evaluate the cumulative environmental impacts of such products across its entire life cycle (International Organization for Standardization, 2006). Agricultural LCA studies are particularly affected by variability, as environmental results may depend on annual climatic conditions, crop yields, input use, and farm management practices. This variability normally could be considered on two complementary perspectives: temporal variability across production years and variability among producers within the same sector. Multiple studies have shown that relying on a single production year may lead to misleading results, especially for perennial crops, whose yields, inputs, and environmental impacts vary across the production cycle (Bessou et al., 2016). Similarly, site specificity and inter-annual variability have been identified as key aspects in agricultural LCA, supporting the need for multiple year inventory data (Cabot et al., 2023). So, when LCA results are intended to describe a sectoral system, data collection from a representative sample of operators is crucial. Previous studies in Europe have reported varied environmental performances for dehydrated alfalfa supply chains. For instance, an LCA in Spain found a relatively high global warming impact per tonne of dehydrated alfalfa, mostly influenced by relevant energy use in processing (Gallego et al., 2011). In France, a recent footprint study highlighted improvements over time but still documented a sizeable carbon footprint, attributed to high drying energy demands historically reliant on fossil fuels as coal and lignite (Thiébeau et al., 2023). Although Italy is among the leading producers of alfalfa, a comprehensive life cycle assessment of dehydrated forage produced in Italy has not yet been conducted. This study was developed in collaboration with AIFE, the Italian Association of Dehydrated Forage Producers, that represents most of dehydrated forage producers in Italy, accounting for over 95% of national production. It is also the second largest association in Europe in terms of production volume. AIFE's members operate 30 processing plants across eight Italian regions, covering approximately 90.000 ha of cultivated land (AIFE, 2021). This study represents the first third party verified assessment of this kind conducted within the AIFE-associated dehydrated forage sector in Italy.

1.3. Motivation of the study

This study aims to fill the gap by conducting the first comprehensive LCA of dehydrated alfalfa forage production in Italy, developed in accordance with internationally recognized ISO 14040 and ISO 14044 standards. While previous studies have explored the environmental performance of forage systems in other European contexts, notably in France and Spain, no such systematic assessment exists for the Italian supply chain, despite its relevance at both national and European levels (Bacenetti et al., 2018). The primary objectives of this study are:

(1). To quantify the environmental impacts associated with the production of 1 tonne of dehydrated alfalfa hay (baled forage) in Italy, by applying a structured LCA approach that identifies the most impactful life cycle stages ("hotspots") along the supply chain. This includes evaluating the energy and material flows involved in agricultural operations, transportation, dehydration processes, and final product distribution.

(2). To evaluate the broader environmental contributions of alfalfa cultivation, by exploring co-benefits that are often overlooked in standard LCA frameworks. These include effects on carbon uptakes, nitrogen fixation, and reduced need for synthetic inputs.

By addressing these two objectives, the study aims to provide a quantitative foundation for understanding the environmental impacts of dehydrated alfalfa production among AIFE producers. The results are intended to support data-driven strategies for improving the sector's sustainability performance and guiding decision-making along the value chain. In particular, the study offers downstream stakeholders, such as feed manufacturers, livestock producers, and sustainability analysts, reliable data for calculating the carbon footprint of animal feed products, assessing environmental trade-offs, and meeting reporting or certification requirements. The study also aims to highlight potential trade-offs between the agronomic and environmental benefits of alfalfa cultivation and the environmental costs of industrial dehydration processes, particularly in terms of energy use and emissions.

2. Materials and methods

2.1. Goal and scope definition of LCA analysis

2.1.1. Goal of the study

The goal of the study is to assess the environmental performance of dehydrated alfalfa forage produced in Italy, with a focus on identifying impact hotspots and potential improvements. The assessment is a "cradle-to-gate with options" analysis, meaning it covers the supply chain from initial inputs up to the factory gate of the dehydrated forage product, including the distribution stage to a typical customer. This scope goes through all major stages from cultivation of alfalfa in the field through to the delivery of the dried forage in packaged form (bale format). The study adheres to ISO 14040/44 guidelines for goal and scope definition, inventory analysis, impact assessment and interpretation. It also aligns with the Product Category Rules (PCR) of the Made Green in Italy scheme, from the Italian Ministry of Environment and Energy Security (Ministero dell'Ambiente e della Sicurezza Energetica, 2023). The environmental impacts assessed in this study include all categories defined by the Environmental Footprint 3.1 impact assessment method (European Commission, 2021), with particular attention to climate change, fossil resource use, and particulate matter emissions, in line with the priorities highlighted in the PCR mentioned above.

2.1.2. Functional unit

The functional unit is defined as 1 tonne of dehydrated alfalfa-based forage, at 87% dry matter, sold in bales and ready for market. The mass of packaging materials is not included in the one-tonne reference flow; however, the environmental impacts associated with the production and transport of packaging materials are included within the system boundaries (Associazione Italiana Foraggi Essiccati, 2016). All results are expressed by this functional unit. The choice of one tonne of product as the functional unit does not allow for straightforward comparisons with other feed products or studies from other countries, as it must be adjusted for nutritional properties such as protein content. On the other hand, it represents a typical output quantity for forage dehydration plants and is highly relevant for farmers and stakeholders in the feed industry. At present, there is no established methodology for defining a functional unit based on nutritional values for this type of product. This contrasts with other categories, such as milk, where functional units like kilograms of FPCM (Fat and Protein Corrected Milk) are commonly used (McAuliffe et al., 2020; European Dairy Association, 2019).

2.1.3. System boundaries

The system boundaries (Fig. 1) include all processes required to produce and deliver the functional unit, divided into the following life cycle stages:

Cultivation of alfalfa: from land preparation and seeding through crop growth and field operations across multiple harvests (alfalfa is a multi-cut, perennial crop typically lasting 3–5 years in production). This stage encompasses: production and supply of agricultural inputs (e.g. fertilizers, crop protection agents, seeds) and on-field fuel use and emissions from agri-machine operations. The corresponding inventory data and machinery parameters are reported in Section 2.2.

Irrigation is not included because, in Italy, alfalfa cultivation is rainfed. Any liming or other soil amendments, if applied, are included in the inputs. For these inputs, both direct and indirect emissions are considered, consistently with the approach adopted for the other purchased products.

Transport of alfalfa from field to processing facility: after each cut, alfalfa is usually field-dried through sun-curing for at least 24–72 h to reduce moisture content (Associazione Italiana Foraggi Essiccati, 2016). This practice represents a typical feature of the Italian production system, as it exploits a natural pre-drying phase that significantly affects the energy consumption of the subsequent industrial dehydration process and the transport phase. The inventory data and calculations concerning field-drying, moisture content, and transport distances are reported in Section 2.2.

Industrial dehydration process: at the processing plant, alfalfa bales are further dried using high temperature forced air in large rotary dryers. In the Italian system, the energy source for drying is primarily natural gas, combusted on-site to generate hot air, with electricity used for fans, conveyors, and other machinery. This stage is typically the most energy intensive. Within this module we include: combustion of natural gas (and any other fuels if used in some plants) and associated direct emissions; production and upstream supply chain of those fuels (extraction, refining, and transport of natural gas, accounted via upstream datasets); consumption of grid electricity and/or on-site renewable electricity (noting that some facilities have photovoltaic installations contributing a portion of electricity demand). The dried alfalfa is typically compressed into large bales (e.g. 400–500 kg big bales or smaller bales) and secured, often using steel wire ties or plastic strapping. The LCA includes the production of packaging materials (e.g. plastic twine) and their transport to the forage plant, as well as any energy used in baling/packaging operations. The product under study is baled dehydrated forage; pelletized alfalfa was excluded from this analysis, as pellet production is a separate process with additional energy use (and was not common to all facilities). By excluding pellets and focusing on bale products, we adhere to a uniform product system and relevant feed product category rules.

Distribution to market: following packaging, the product is transported from the processing plant to a representative customer gate. We developed multiple scenarios based on the sales data of the company analysed. Inputs are mainly road transport and sea transport.

2.1.4. Exclusions and cut-off criteria

The use and end-of-life stages are excluded because dehydrated alfalfa is an intermediate feed product and these stages are outside the scope defined by the applicable PCR. Office activities and the production of capital goods, including buildings, infrastructure and machinery, were excluded. Pellet production was also excluded, as it requires an additional processing stage and was not common to all sampled facilities. Irrigation was not included because alfalfa cultivation in the systems analysed was rainfed. No percentage-based cut-off threshold was applied in addition to these defined exclusions. All principal material and energy flows associated with the included life-cycle stages were considered.

2.1.5. Allocation procedures

No allocation between co-products was necessary in this study, since the system's primary product is dehydrated alfalfa hay. All alfalfa crop output goes into the forage product, and no other co-product is generated at the processing stage. The functional unit is served entirely by the

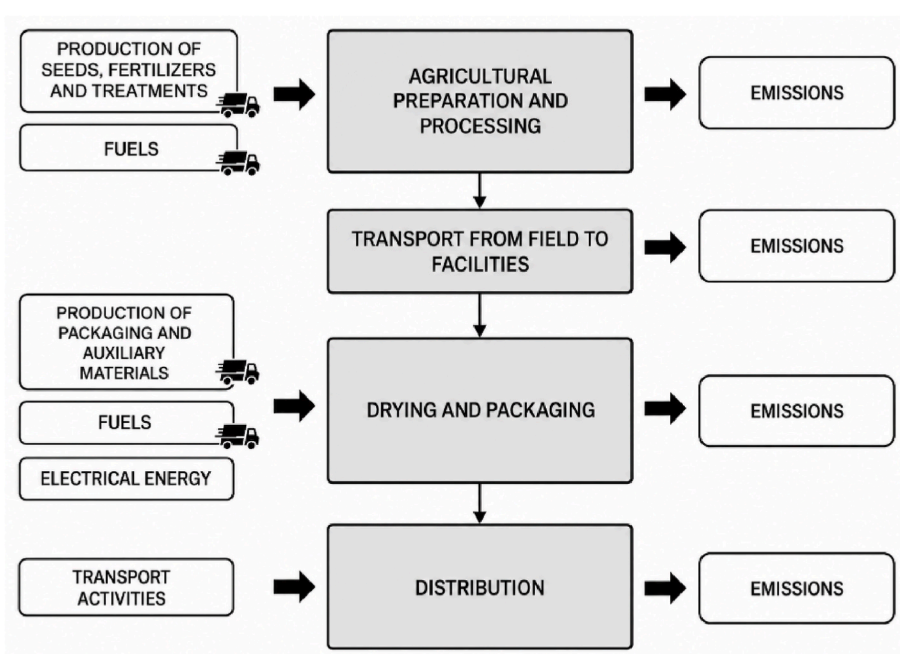

Fig. 1. System boundary and main life cycle stages considered in the cradle-to-gate LCA of dehydrated alfalfa forage. The diagram shows the main input flows, process stages, intermediate transport, distribution activities, and associated emissions included in the assessment.

single output product. Primary material and energy flows were assigned directly to the studied product whenever process-specific data were available. Electricity consumption was directly measured for the relevant production process in two facilities. For the remaining facilities, where dedicated metering was unavailable, electricity consumption was allocated to dehydrated alfalfa production on a mass basis. The same allocation was performed for the other flows. For background processes involving recycled materials, the Ecoinvent cut-off system model was applied. Under this approach, primary production bears the impacts associated with the production of virgin materials, while recycled materials entering a subsequent product system bear only the impacts associated with recycling and recovery processes. No avoided burden credits were assigned to the studied product.

2.1.6. Data quality

Data quality was assessed considering completeness, reliability, temporal, geographical and technological representativeness, consistency. Primary foreground data were collected directly from the sampled facilities and their associated agricultural production systems using a standardized data collection template. These data included production volumes, crop yields, agricultural inputs, fuel and electricity consumption, transport activities and packaging materials. Temporal representativeness was addressed through the collection of data over the 2019–2023 period, where inter-annual variability may significantly affect yields, inputs and environmental performance. Geographical and technological representativeness were addressed through the sampling procedure described in Section 2.2.1. Completeness and consistency of primary data were supported by a preliminary pilot test of the data collection tool, direct interactions with the participating companies and on-site visits. The collected data and related procedures were subsequently reviewed through an independent third-party verification process. Primary operational data were considered of relatively high quality because they were facility-specific and directly related to the processes under study. Conversely, background processes were modelled using secondary datasets from Ecoinvent and other recognized sources and are therefore subject to the inherent uncertainty and representativeness limitations of those databases.

2.2. Life cycle inventory (LCI)

2.2.1. Case selection and sampling approach

To ensure that the LCA study reflects the full supply chain represented by AIFE, a structured sampling procedure was adopted. The methodology follows the guidelines provided in Annexes 1 and 2 (Section 4.4.6) of the Product Environmental Footprint (PEF) Recommendation (EU) 2021/2279, issued by the European Commission on December 15, 2021 (European Commission, 2021). This is also relevant for addressing variability in agricultural LCA in a formal way. When LCA results are intended to describe a sectoral system, data collection from a representative sample of operators is important to account for differences in management, technologies and operational conditions (Avadí et al., 2016).

The target population comprises the 23 AIFE member companies involved in the production of dehydrated alfalfa forage for animal feed. According to PEF guidelines, the number of subpopulations (N_{sp}) is determined by the product of:

- the number of countries where production sites are located (g);
- the number of different processing technologies/agronomic practices (t);
- the number of production capacity classes (c).

Geographical Coverage (g): since all production sites are in Italy, we considered the parameter equal to one ($g = 1$).

Technology (t): although the agronomic practices for alfalfa cultivation are homogeneous across the population, the drying process can vary in terms of plant configuration and energy source. Two main technologies are in use:

- Rotary drum dryers: material passes through a rotating cylinder exposed to hot airflow.
- Belt dryers: material is spread on a perforated belt with hot air passing through.

Regarding the energy source, all companies use natural gas as the main thermal energy vector, with no use of biomass or coal/lignite. A structured interview with AIFE's President and Director confirmed that only one member company uses a belt dryer. Thus, for this study, we considered the parameter equal to one ($t = 1$).

Production Capacity (c): based on video-call interviews conducted with members of the association (AIFE) and on a preliminary analysis of the collected dataset, it emerged that plant production capacity does not directly affect the main environmental flows, such as energy consumption. The primary drivers influencing energy consumption were identified as field management practices and the moisture content of the biomass delivered to the dehydration plant. As expected, energy demand increases with the amount of water that must be removed during the industrial dehydration process. A strong positive linear correlation (Pearson index > 0.7) was observed in the sampled companies between moisture content at plant inlet and thermal energy consumption (Pearson index $= 0.73$). Even if production capacity does not directly affect the main environmental flows, using the data collected through the interviews, companies were classified based on a production threshold of 50,000 tonnes/year. About 85% of AIFE members fall below this threshold, while 15% exceed it. Therefore, we considered the parameter equal to one, ($c = 1$).

Applying PEF guidelines methodology, given the values $g = 1$, $t = 1$ and $c = 1$:

$$N_{sp} = g\ x\ t\ x\ c = 1$$

The subpopulation is therefore equivalent to the entire population. Then following the PEF guidelines, the sample size (N_{ss}) for a subpopulation of 23 companies (n_{sp}) is calculated as:

$$\sqrt{n_{sp}} = \sqrt{23} = 4.79 \approx 5$$

Using the sampling procedure described above, five AIFE member companies were selected. Considering that AIFE members produce between 585.000 and 665.000 tonnes of dehydrated alfalfa annually, the selected sample represents approximately 20,4% to 23,2% of the total national production. The sample also ensures representation of the main geographical areas involved in the sector (see Fig. 2). Furthermore, in order to ensure the highest possible accuracy in sample selection, companies were chosen based on their ability to represent the regional geographical distribution of the identified population (Table 1).

2.2.2. Data sources and inventory data

Primary data were collected over the five-year period 2019–2023 for both the agricultural production and industrial dehydration stages. For the agricultural stage, annual data included crop yields, number of cuts, agricultural inputs and fuel consumption associated with field operations. This multi-year approach was particularly relevant for capturing inter-annual variability in agricultural production due to climatic conditions, crop productivity and management practices. For the industrial stage, annual data included dehydrated alfalfa production volumes, electricity consumption and fuel use. Although inter-annual variability is generally less pronounced for industrial processing than for agricultural production, the five-year dataset also allowed year-to-year variations in processing performance to be considered (Bessou et al., 2016; Cabot et al., 2023). In total, 25 plant-years of data were analysed. For each facility, detailed information was obtained on annual production of dehydrated alfalfa (tonnes), cultivation practices, agricultural inputs,

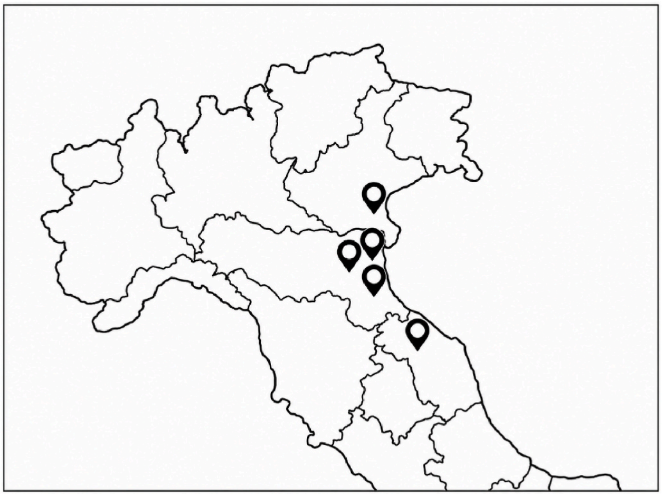

Fig. 2. Geographical location of the five processing plants included in the data collection. The markers indicate the facilities selected within the AIFE-associated sample on Italy administrative map.

Table 1
The table reports the number of companies belonging to the AIFE population and the number of facilities included in the LCA data collection for each region.

Administrative Regions	*AIFE companies*	*Sampled companies*
Emilia-Romagna	13	3
Marche	3	1
Veneto	2	1
Lombardia	1	0
Abruzzo	1	0
Lazio	1	0
Toscana	1	0
Umbria	1	0

energy and fuel consumption. For the cultivation stage, primary data included annual yields, number of cuts, agricultural inputs, and fuel consumption associated with field operations. The field operations and machinery parameters used to model the cultivation inventory are summarized in Table 2.

Depending on the farm configuration, forage chopping and loading were performed either simultaneously using forage wagons equipped with chopping and loading systems or as two separate operations. In the latter case, the forage was first chopped and subsequently loaded into

Table 2
Agricultural field operations included in the cultivation phase, reporting the tractor power range, type of implement used, and hourly fuel consumption range recorded for the farms included in the data collection.

Field operation	Implement type	Tractor power (hp)	Fuel consumption (l/h)
Primary tillage	Mouldboard plough (3–4 furrows)	215–330	27–37
Secondary tillage	Disc cultivator (4 m working width)	95–155	15–30
Seedbed preparation	Vibrating tine harrow (6 m working width)	215–330	18–21
Sowing	Combined seed drill	95–155	15–30
Fertiliser application	Centrifugal fertiliser spreader	105–130	11–12
Mowing	Disc mower (7.4–9 m working width)	215–280	20–23
Raking	Belt rake (9.5 m working width)	120–150	9–10
Forage chopping and loading*	Forage wagon (52–60 m^3 capacity)	150–190	8–10

semi-trailers using dedicated equipment, while transport to the dehydration facility was performed by road tractors. These alternative configurations were modelled according to the operational data provided by each sampled facility. Notably, none of the farms used synthetic nitrogen fertilizers on alfalfa, as the crop is a legume. Pesticide use was absent. Yields ranged from 10 to 15 tonnes of dry matter per hectare annually, with approximately four cuts per year. At the processing stage, each facility provided data on electricity and fuel use per tonne of dehydrated output. All five plants used natural gas as the primary energy source for drying. Drying energy intensity (kWh/tonne) varies depending on the moisture content of incoming forage. By defining the dry matter content as reported below and assuming that dry matter losses are negligible, the following relationship can be established (Equation 1):

$$M_{in}(1 - w_{in}) = M_{out}(1 - w_{out})$$

$$w_{in} = 1 - \frac{1 - w_{out}}{r}$$

Equation 1. Inlet moisture content ratio.

Where:

M_{in} = *inlet mass to the dehydration facility, representing the transported product*

M_{out} = *outlet mass from the dehydration facility*

w_{in} = *inlet moisture content*

w_{out} = *outlet moisture content* (13%)

r = *moisture reduction due to the industrial process* $= M_{in}/M_{out}$

Based on the collected data, an average mass reduction ratio of 1.25 (r) was observed at the dehydration plant. This value was calculated as the arithmetic mean of the results recorded over five years of observation (2019–2023) across the analysed farms. Applying the relationship above, an inlet moisture fraction of 30% (w_{in}) was calculated. Assuming an average moisture content of 75% immediately after cutting, the moisture reduction occurring during field drying was estimated at 45%. Facilities equipped with photovoltaic systems met up part of their electricity demand through on-site solar production. Emissions from combustion processes (e.g., CO_2, NO_x) were not directly measured but were estimated using fuel usage data and standard emission factors. For transport from the cultivation fields to the dehydration facilities, the average distance was 20.3 km. For each facility, field-to-plant distances were weighted according to the corresponding cultivated area. For the packaging and distribution stages, inventory data included the quantities of packaging materials used per tonne of product and average transport distances. Secondary data for background processes were taken from the Ecoinvent database v3.8 (Table 3). Where possible, region-specific data were used.

Table 4 presents the main inventory flows and their corresponding units. Inventory data are reported through descriptive statistics calculated separately for temporal variability and between-firm variability. Temporal variability was assessed by first calculating annual averages across the sampled companies and then deriving the mean (μ_{years}), minimum (min_{years}), maximum (max_{years}), standard deviation (σ_{years}), and coefficient of variation (CV_{years}) across the five production years. Between-firm variability was assessed by first calculating five-year averages for each company and then deriving the mean (μ_{firms}), standard deviation (σ_{firms}), and coefficient of variation (CV_{firms}) across the sampled companies. The coefficient of variation was calculated as the ratio between standard deviation and mean values (Cabot et al., 2023) This approach allows temporal variability and variability among operators to be described separately while preserving the confidentiality of firm specific data that the authors could not report (Thom et al., 2026).

2.2.3. *Data collection procedures*

Primary data were collected using a structured excel-based data

Table 3
Ecoinvent v3.8 datasets used for modelling the main input flows across the life cycle stages of dehydrated alfalfa forage. All datasets are reported according to the Cut-Off system model and unit process approach.

Life cycle stage	Flow description	Ecoinvent 3.8, Cut-Off, Unit Process
Cultivation of alfalfa	Alfalfa seeds	Clover seed, Swiss integrated production, for sowing {CH}
	Transport of seeds and raw materials	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
	Field operations	Diesel combustion {IT}
Transport to processing plant	Transport of alfalfa from cultivation sites to processing plants	Transport, tractor and trailer, agricultural {CH}
Industrial dehydration process	Thermal energy	Heat, natural gas {IT}
	Grid electricity	Electricity, medium voltage {IT}
	Electricity from photovoltaic system	Electricity, low voltage {IT}
	Internal transport	Diesel combustion {IT}
Packaging	Twine	Polypropylene, granulate {RER}
		Polyethylene terephthalate, granulate, amorphous {RER}
	Transport of packaging materials	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
Distribution to customer	Road transport in Italy and Europe	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
	Overseas road transport	Transport, freight, lorry >32 metric ton, EURO5 {RoW}
	Overseas maritime transport	Transport, freight, sea, bulk carrier for dry goods {GLO}

collection tool, developed jointly by the research team and the AIFE staff. The spreadsheet was designed to capture all relevant operational, agronomic, energy, and logistics data required for the life cycle inventory (LCI) of dehydrated alfalfa forage production. Before full deployment, the data collection tool was tested and validated in collaboration with a pilot company to ensure clarity, feasibility, and completeness. Following this pilot phase, the finalized template was distributed to the remaining four facilities in the sample. To ensure data quality and consistency, two on-site visits were conducted at selected processing plants. All collected primary data and related procedures were subsequently reviewed, audited and verified by an independent third-party in accordance with ISO 14044 requirements. This verification process supported the issuance of a formal conformity and validation statement, confirming that the data collection and treatment followed internationally accepted standards for LCA studies.

2.2.4. Assumptions and limitations

One company was selected for inclusion in the sample; however, it subsequently ceased operations, preventing completion of the audit and data verification process. A replacement company was quickly identified, but it functioned exclusively as a processing facility and did not oversee any direct agricultural production. As a result, it was not possible to collect agronomic data from this site. For consistency, primary data for the “cultivation of alfalfa” stage were instead taken from the most comparable facility in the sample, based on geographic location and operational characteristics. Another important assumption pertains to the transportation stage. Distances were estimated using a weighted average of field-to-plant distances, based on field area, under the assumption of a linear relationship between cultivated surface and production volume. Impact calculations were then carried out using tonne-kilometres as the reference unit. While commonly used, tonne-kilometre-based approaches have known limitations, particularly due to uncertainties in load efficiency and the inability to account for empty return trips. This methodology was adopted because not all sampled companies were able to provide specific fuel consumption data for transport vehicles. Future improvements should focus on collecting detailed fuel consumption data for the transport phase, with a preference for an energy-based approach over an activity-based one.

2.3. Life Cycle Impact Assessment (LCIA)

For the Life Cycle Impact Assessment (LCIA) phase, the study employed the midpoint indicators defined by EF 3.1 method. This choice was primarily driven by the desire to ensure compliance with the Product Environmental Footprint Category Rules (PEFCR) established under the "Made Green in Italy" scheme (Ministero dell’Ambiente e della Sicurezza Energetica, 2023). In particular, the PEFCR highlights Climate Change, Particulate Matter Formation, and Resource Use, Fossil as priority impact categories for this product group. The EF 3.1 method provides a comprehensive set of impact categories, aligned with the most recent European methodological recommendations. Results were first computed individually for each of the five sampled facilities to assess inter-site variability. A production-weighted average was then calculated, assigning weights based on the relative annual output of each facility. This approach ensured that the final results reflect a

Table 4
Descriptive statistics of the main inventory flows used to assess temporal and between firm variability. Temporal variability is described through the mean, minimum, maximum, standard deviation and coefficient of variation across the five production years, while between-firm variability is described through the mean, standard deviation and coefficient of variation across the sampled companies.

Inventory flow	μ_{years}	min_{years}	max_{years}	σ_{years}	μ_{firms}	σ_{firms}	CV_{years}	CV_{firms}
Cultivated area (ha)	1.452	1.367	1.509	53	1.610	1.121	4%	70%
Average size of fields (ha/nr)	12,75	11,33	15,64	1,61	12,74	4,91	13%	39%
Annual fresh matter yield (ton/ha)	10,57	8,84	12,35	1,13	10,57	1,72	11%	16%
Diesel use for soil preparation (lt/FU)	4,24	3,01	4,86	0,68	4,09	1,27	16%	31%
Diesel use for sowing (lt/FU)	2,50	2,31	2,79	0,17	2,43	1,29	7%	53%
Diesel use for soil preparation and sowing (lt/FU)	6,74	5,48	7,65	0,72	6,52	0,53	11%	8%
Seed quantity used (kg/FU)	4,13	3,71	4,57	0,30	4,13	1,08	7%	26%
Diesel use for cutting and collection (lt/FU)	5,94	4,71	7,07	0,81	5,92	2,10	14%	35%
Average truck load per trip (ton/trip)	10,73	9,91	11,33	0,54	10,73	2,75	5%	26%
Kilometers travelled (km/FU)	3,59	3,28	3,95	0,26	3,56	1,22	7%	34%
Distance field-to-plant (km/trip)	20,32	19,72	22,01	0,85	20,32	11,13	4%	55%
Fuel use (natural gas) (Smc/FU)	35,42	25,58	48,44	7,35	35,42	17,55	21%	50%
Fuel use (diesel) for internal logistic (lt/FU)	1,54	1,35	1,78	0,15	1,54	0,56	10%	36%
Electricity consumption (grid + photovoltaic) (kWh/FU)	77,51	71,99	84,91	4,59	77,51	35,92	6%	46%
Share of photovoltaic electricity (%)	0,17	0,14	0,20	0,02	0,17	0,14	13%	83%
Moisture reduction due to industrial dehydratation (r)	1,24	1,19	1,30	0,04	1,25	0,09	3%	7%
Quantity of packaging materials used (kg/FU)	1,28	0,97	1,59	0,21	1,23	0,57	17%	46%

representative industry-average profile for the Italian dehydrated forage sector, as represented by AIFE member companies.

The key impact categories analysed in this study include:

Climate Change (Global Warming Potential, GWP100): this category quantifies GHG emissions and is expressed in $kgCO_2$ equivalents per functional unit. Fossil GWP is reported separately, dividing biogenic and land-use change (LUC) GHG emissions. In our case, biogenic flows are only associated with seed production. Carbon sequestration from crop cultivation is reported separately, following PEF guidance. Land-use change emissions are negligible, as alfalfa is cultivated on existing cropland.

Particulate Matter Formation (PM): reported in terms of human health impacts (disease incidence), this category captures emissions of primary particulates and precursor substances such as NH_3 and NO_x. These emissions arise primarily from field operations and combustion sources.

Resource Use, Fossil: this indicator measures the depletion of fossil energy resources (oil, natural gas, coal), expressed in megajoules (MJ) based on lower heating value. It represents the cumulative fossil energy demand of the system and is especially pertinent given the high energy requirements of the drying phase.

All analyses were conducted using SimaPro LCA software (v9).

2.4. Other environmental indicators assessment

In addition to the standard outputs of the LCA model, this study includes a quantitative assessment of potential environmental contributions associated with alfalfa cultivation that are not fully captured within the core LCA impact categories. These aspects were evaluated using literature sources and external models, and are reported separately in accordance with the PEF guidelines, which recommend presenting such results in a dedicated section titled “Additional Technical Information” (European Commission, 2018). This approach ensures methodological transparency and avoids misinterpretation, while still providing insights into environmental processes such as carbon removal and storage.

2.4.1. Carbon uptake in aboveground biomass

Like other photosynthetic plants, alfalfa captures atmospheric CO_2 through photosynthesis, converting it into energy-rich organic compounds using solar energy. These sugars serve not only as an immediate energy source for cellular metabolism but also as fundamental building blocks for synthesizing structural and storage compounds such as cellulose, starch, proteins, and lipids. The carbon fixed during photosynthesis is therefore incorporated into a wide range of organic molecules within the plant biomass. It is feasible to estimate the amount of carbon temporarily stored in the harvested aerial biomass: this can be done by applying the methodology described below (Equation 2), using site-specific production data and standard biomass carbon content factors (ISPRA - Istituto Superiore per la Protezione e Ricerca Ambientale, 2022a; Eve et al., 2014).

CS_C = *Carbon stock in harvested biomass* $[ton\ C\ ha^{-1} year^{-1}]$
CS_{CO_2} = *Carbon stock in harvested biomass* $[ton\ CO_2\ ha^{-1} year^{-1}]$
Y_{dm} = *Dry matter yield* $[ton\ ha^{-1} year^{-1}]$
HI = *Harverst index* [*dimensionless*]
CF = *Carbon fraction in biomass* [*dimensionless*]
CO_2MW = *molecular weight ratio between carbon dioxide* [*dimensionless*]

$$CS_C = Y_{dm}/HI \times CF$$

$$CS_{CO_2} = Y_{dm}/HI \times CF \times CO_2MW$$

Equation 2. Carbon stock in harvested biomass.

Based on the data for the harvested and useable product, which qualify as primary data, as they are directly measured by the processing facilities, the harvest index (HI) was set to 1. This assumption reflects that the entire aboveground biomass is harvested. The carbon fraction (CF) in the dry biomass was set at 47%, in line with IPCC guidelines (Simon and Walsh, 2006). A slightly more conservative value of 45% is also found in the literature (Olson, 1983; Eve et al., 2014). The molecular weight ratio between carbon dioxide (CO_2) and elemental carbon (C) is calculated based on their respective molecular weights and is equal to 3,67.

2.4.2. Carbon uptake in belowground biomass

In addition to aboveground carbon uptake, alfalfa also contributes significantly to belowground carbon sequestration through its extensive root system. Unlike the harvested biomass, the root biomass remains in the soil after the crop cycle and gradually decomposes, contributing to the maintenance and enrichment of soil organic matter (Lal, 2004). To estimate the amount of carbon sequestered in the root system, it is necessary to introduce the following parameters, which allow for a quantitative assessment of belowground biomass accumulation (Equation 3).

$R:S$ = *Indice Root : Shoot* [*dimensioless*]
Y_{peak} = *Peak production value* (*single cut*) $[ton\ ha^{-1}]$

$$CS_C = Y_{peak}/HI \times CF \times R:S$$

$$CS_{CO_2} = Y_{peak}/HI \times CF \times R:S \times CO_2MW$$

Equation 3. Carbon stock in belowground biomass.

The productive composition of alfalfa is highly variable and strongly influenced by several factors, foremost among them climatic conditions. The first harvest of the year typically yields significantly more forage than subsequent cuts. On average, the first cut accounts for approximately 35% of the total annual forage production (Bortolazzo et al., 2016). The Root:Shoot ratio is a measure of biomass distribution between belowground (roots) and aboveground (stems and leaves) parts of a plant. A Root:Shoot ratio of 0,87 was adopted, based on values reported in the literature. The ratio was derived from established carbon accounting methods for agricultural systems (Eve et al., 2014; West et al., 2010), which provide a framework for estimating belowground biomass starting from aboveground production, harvest index, and biomass carbon content. This approach provide an inventory based estimate of belowground carbon uptake rather than use a site specific measurement of root biomass. Italian experimental data on lucerne root biomass are available and report higher values than those estimated in the present study. Specifically, the belowground biomass values estimated here range from 1.77 to 3.20 tonDM/ha, while available Italian experimental evidence reports values approximately 1.7–2.3 times higher (Annicchiarico, 2007). This comparison suggests that the estimate adopted here is conservative. Unlike the approach used for calculating carbon stock in harvested biomass, where a harvest index (HI) of 1 was assumed, an HI value of 0,95 was used for estimating root biomass. This adjustment accounts for the portion of the stem that remains unharvested in the field.

2.4.3. Potential GHG savings from reduced nitrogen fertilization of subsequent crops

Alfalfa is a nitrogen-fixing legume and is generally cultivated without synthetic nitrogen fertilizer. This absence of nitrogen fertilizer application during alfalfa cultivation is already reflected in the foreground inventory and is therefore not considered an additional environmental benefit in the present calculation. The additional indicator assessed here refers instead to the potential residual nitrogen benefit provided by alfalfa to a subsequent crop in rotation. Following the termination of an alfalfa stand, part of the nitrogen associated with belowground biomass and crop residues can become available to the following crop, potentially reducing its requirement for synthetic nitrogen fertilizer. No specific crop rotation sequence or subsequent crop was modelled in this study. The calculation was therefore developed as a scenario-based estimate using literature values for the nitrogen credit associated with alfalfa preceding an arable crop. This reduction not only lowers direct N_2O emissions from fertilizer applications in the field but also limits the upstream greenhouse gas emissions associated with the production and transportation of such chemical inputs. The industrial synthesis of nitrogen fertilizers, particularly through the Haber-Bosch process, is highly energy-intensive and relies heavily on natural gas, contributing to greenhouse gas emissions and climate change. Assuming a crop rotation scenario involving alfalfa and arable crops, and that a certain quantity of synthetic nitrogen fertilizer per hectare is avoided due to the nitrogen-fixing capacity of alfalfa, the methodology outlined below can be used to estimate the corresponding greenhouse gas (GHG) emission savings (Equation 4).

$F_{SN} =$ *avoided application of synthetic nitrogen fertilizer* $\left[kgN\,ha^{-1}year^{-1}\right]$

$EF_{SN} =$ *EF for direct emissions from synthetic nitrogen fertilizers* $\left[kgN_2O - N\,kgN^{-1}\right]$

$EF_{CR} =$ *EF for direct emissions from crop residues* $\left[kgN_2O - N\,kgN^{-1}\right]$

$Frac_{GASF} =$ *Fraction of nitrogen that volatilizes as* NH_3 *or* NO_x $\left[(kgNH_3 - N + NO_x - N)kgN^{-1}\right]$

$EF_{VOL} =$ *EF for atmospheric deposition* $\left[kgN_2O - N(kgNH_3 - N + NO_x - N)^{-1}\right]$

$E1_{NO_2} =$ *avoided emissions due to the non application of synthetic fertilizer* $[kgN_2O - N]$

$N_2OMW =$ *ratio between the molar mass of* N_2O *and the molar mass of N* $[kg\,N_2O\,kgN_2O - N]$

$E2_{CO_2} =$ *avoided emissions due to the non − production of synthetic fertilizer* $[kgCO_2]$

$E_{CO_2} =$ *avoided emissions due to the non − use of synthetic fertilizer* $[kgCO_2]$

$$E1_{N_2O} = [F_{SN} \times (EF_{SN} - EF_{CR}) + F_{SN} \times Frac_{GASF} \times EF_{VOL}] \times N_2OMW$$

Equation 4. Avoided emissions due to the non application of synthetic fertilizer.

In this study, emission factors (EFs) related to nitrogen inputs and losses are adopted in accordance with the IPCC 2006 Guidelines and its 2019 Refinement, Tier 1 approach (IPCC - International Panel for Climate Change, 2019). Specifically:

- The direct emission factor for synthetic nitrogen fertilizer application is set at 0.016 kg N_2O–N per kg of N applied.
- The direct emission factor for nitrogen present in crop residues is assumed to be 0.006 kg N_2 = -N per kg of N in residues.
- For nitrogen volatilization, the default emission factor is 0.11 (kg NH_3–N + NO_x-N) per kg of N applied.
- For indirect N_2O emissions via atmospheric deposition, the emission factor is 0.010 kg N_2O–N per kg of volatilized N (NH_3 + NO_x).
- To convert N_2O–N into N_2O, a molecular weight ratio of 44/28 is applied. Furthermore, to express N_2O emissions in terms of CO_2-equivalents, a Global Warming Potential (GWP100) of 273 is used, following the most recent IPCC Sixth Assessment Report (IPCC - International Panel for Climate Change, 2023).

The estimated nitrogen credit is reported as additional environmental information and is not included as a credit in the LCIA results of dehydrated alfalfa, since the potential fertilizer saving occurs in a subsequent crop outside the system boundaries of the present study.

3. Results

3.1. Life Cycle Impact Assessment (LCIA) results

LCIA results are reported in Tables 5 and 6. In Table 5, only the three impact categories identified as priorities by the PCR are reported, namely Climate Change (CC), Particulate Matter Formation (PMF), and Fossil Resource Use (RU-f).

Regarding the climate change impact category, which the PCR also identifies, together with Particulate Matter Formation and Fossil Resource Use, as a priority impact category, the production of 1 tonne of dehydrated alfalfa forage in Italy was found to result in a Global Warming Potential (GWP) of 243 kg CO_2eq/t. This is the production weighted mean across the surveyed facilities. There was noticeable variability: individual facility results ranged from about 202 kg CO_2eq/t up to 361 kg CO_2eq/t, largely due to differences in energy efficiency and feedstock moisture as described below. Despite this range, all facilities are within the same order of magnitude, and the weighted average (used as the best estimate) falls in the lower end of that range (Fig. 3).

The standard deviation of the analysis results is 63.8 kg CO_2eq/t. A similar variability can also be observed for the other priority impact categories, particularly articulate matter formation (PMF) and fossil resource use (RU-f). For PMF, the arithmetic mean across the surveyed facilities is 7.83E−06 disease inc./t, with a standard deviation of 1.76E−06. For RU-f, the arithmetic mean is 3940 MJ/t, with a standard deviation of 927 MJ. The contribution analysis shows that climate change impacts are mainly driven by the industrial dehydration stage, which accounts for approximately 47% of total GWP. This is primarily related to the use of natural gas for thermal energy generation during the drying process. Distribution is the second most relevant contributor, accounting for around 29% of the total GWP, followed by alfalfa cultivation, which contributes approximately 21%. The dominant contribution for particulate matter formation (PMF) comes from the distribution stage, which accounts for approximately 70% of the total result. Fossil resource use (RU-f) is mainly associated with the consumption of fossil energy carriers along the industrial dehydration and distribution stage. The main inventory flows driving the three priority impact are diesel use for soil preparation and sowing, diesel use for cutting and collection, natural gas consumption for the dehydration process, and electricity consumption from the grid. They are therefore analysed in greater detail in the following section.

3.2. Other environmental indicators assessment results

3.2.1. Carbon uptake in aboveground biomass

With regard to the uptake in aboveground biomass, the following yield data had resulted, expressed in tonnes of dry matter per hectare. Weighted yield is calculated through production volumes. It can be seen that the national average (Table 7) is in line with the data collected in the present study (ISPRA - Istituto Superiore per la Protezione e Ricerca Ambientale, 2022b, 2022a).

The results are shown in Table 8:

As also explained in details in discussion section, aboveground biomass uptake is reported only as additional technical information and must not used to offset, reduce, or net against the cradle-to-gate GWP result of 243 kg CO_2eq/t. The same is true for belowground biomass values.

3.2.2. Carbon uptake in belowground biomass

Using the same yield data as above, the results of the carbon uptake in the belowground biomass are reported in Table 9.

3.2.3. Potential GHG savings from reduced nitrogen fertilization of subsequent crops

Assuming a crop rotation scenario between alfalfa and arable crops, it can be considered unnecessary to apply a certain amount of synthetic

Table 5
Arithmetic mean (AA) of the results obtained for the five sampled companies, calculated on the basis of their average performance over the five-year period analysed (2019–2023). The arithmetic mean is reported together with the sample standard deviation, in order to describe the variability among companies.

Impact category	Unit of measure	Total	Cultivation of alfalfa	Transport field/facility	Dehydration process	Packaging	Distribution to market
GWP	kg CO_2 eq	2.70E+02 (±6.38E+01)	4.32E+01 (±1.01E+01)	8.28E+00 (±5.31E+00)	1.45E+02 (±7.03E+01)	6.67E+00 (±5.59E+00)	6.72E+01 (±1.91E+01)
ODP	kg CFC11eq	9.33E-06 (±8.33E-06)	8.93E-07 (±2.24E-07)	1.25E-07 (±8.01E-08)	3.80E-06 (±1.89E-06)	3.20E-06 (±6.95E-06)	1.32E-06 (±4.08E-07)
IRP	kBq U-235 eq	6.82E+00 (±1.51E+00)	6.43E-01 (±2.49E-01)	2.14E-01 (±1.37E-01)	4.04E+00 (±1.99E+00)	9.23E-01 (±7.98E-01)	1.00E+00 (±3.66E-01)
POC	kg NMVOC eq	1.87E+00 (±4.00E-01)	7.36E-01 (±1.77E-01)	7.19E-02 (±4.61E-02)	4.30E-01 (±1.65E-01)	2.29E-02 (±1.95E-02)	6.13E-01 (±2.63E-01)
PMF	Disease inc.	7.83E-06 (±1.76E-06)	7.55E-07 (±2.42E-07)	3.71E-07 (±2.38E-07)	1.05E-06 (±4.83E-07)	2.60E-07 (±2.35E-07)	5.39E-06 (±2.04E-06)
HTP-nc	CTUh	1.85E-06 (±1.93E-07)	6.51E-07 (±2.44E-07)	2.02E-07 (±1.30E-07)	3.81E-07 (±1.75E-07)	4.23E-08 (±3.70E-08)	5.75E-07 (±2.08E-07)
HTP - c	CTUh	7.86E-08 (±1.93E-08)	8.19E-09 (±2.90E-09)	9.74E-09 (±6.25E-09)	2.43E-08 (±1.20E-08)	6.19E-09 (±1.07E-08)	3.02E-08 (±8.50E-09)
AP	mol H+ eq	1.48E+00 (±4.86E-01)	4.68E-01 (±1.15E-01)	5.67E-02 (±3.64E-02)	2.50E-01 (±8.73E-02)	2.52E-02 (±2.12E-02)	6.78E-01 (±4.05E-01)
EP-fw	kg P eq	1.88E-02 (±3.54E-03)	2.92E-03 (±1.28E-03)	1.82E-03 (±1.17E-03)	7.90E-03 (±3.87E-03)	1.91E-03 (±1.68E-03)	4.20E-03 (±1.34E-03)
EUP-m	kg P eq	6.57E-01 (±1.78E-01)	3.84E-01 (±1.23E-01)	1.94E-02 (±1.24E-02)	7.46E-02 (±2.14E-02)	4.80E-03 (±4.11E-03)	1.74E-01 (±8.93E-02)
EUP-t	mol N eq	5.42E+00 (±1.41E+00)	2.46E+00 (±5.92E-01)	2.09E-01 (±1.34E-01)	8.08E-01 (±2.31E-01)	4.88E-02 (±4.19E-02)	1.90E+00 (±9.95E-01)
ET- f	CTUe	1.40E+03 (±2.30E+02)	7.13E+02 (±2.74E+02)	4.13E+01 (±2.65E+01)	1.74E+02 (±6.86E+01)	1.69E+01 (±1.62E+01)	4.56E+02 (±1.32E+02)
LUP	Pt	2.45E+03 (±5.22E+02)	1.52E+03 (±7.10E+02)	9.50E+01 (±6.09E+01)	8.90E+01 (±4.11E+01)	2.10E+01 (±1.76E+01)	7.28E+02 (±3.25E+02)
WDP	m3 depriv.	2.42E+01 (±5.67E+00)	2.13E+00 (±7.78E-01)	7.79E-01 (±5.00E-01)	1.35E+01 (±6.61E+00)	3.84E+00 (±3.25E+00)	3.94E+00 (±1.35E+00)
RU-f	MJ	3.94E+03 (±9.27E+02)	5.88E+02 (±1.47E+02)	9.63E+01 (±6.18E+01)	2.13E+03 (±1.04E+03)	1.91E+02 (±1.65E+02)	9.36E+02 (±2.73E+02)
RU-m	kg Sb eq	4.32E-04 (±6.19E-05)	6.52E-05 (±2.96E-05)	5.79E-05 (±3.71E-05)	1.32E-04 (±8.20E-05)	2.58E-05 (±2.18E-05)	1.52E-04 (±5.22E-05)
GWP-f	kg CO_2 eq	2.75E+02 (±6.31E+01)	4.86E+01 (±1.21E+01)	8.35E+00 (±5.35E+00)	1.44E+02 (±7.00E+01)	6.70E+00 (±5.62E+00)	6.72E+01 (±1.91E+01)
GWP-b	kg CO_2 eq	−4.82E+00 (±2.52E+00)	−5.37E+00 (±2.55E+00)	−8.87E-02 (±5.69E-02)	6.51E-01 (±3.25E-01)	−3.59E-02 (±3.02E-02)	3.02E-02 (±2.08E-02)
GWP-L	kg CO_2 eq	8.75E-02 (±2.12E-02)	9.95E-03 (±4.21E-03)	1.44E-02 (±9.20E-03)	1.46E-02 (±7.28E-03)	7.65E-03 (±9.31E-03)	4.10E-02 (±1.33E-02)

Table 6
Production weighted results calculated using the annual production volumes of the five processing plants and provides the overall representative result of the assessment.

Impact category	Unit of measure	Total	Cultivation of alfalfa	Transport field/facility	Dehydration process	Packaging	Distribution to market
GWP	kg CO_2 eq	2,43E+02	4,97E+01	1,13E+01	1,10E+02	5,06E+00	6,69E+01
PMF	Disease inc.	7,48E-06	9,00E-07	5,08E-07	8,23E-07	1,81E-07	5,07E-06
RU-f	MJ	3,50E+03	6,82E+02	1,32E+02	1,61E+03	1,57E+02	9,21E+02

fertilizers, due to the residual nitrogen provided by the preceding nitrogen-fixing crop. The amount of synthetic fertilizer that can be avoided varies according to the bibliographic references consulted, ranging from 24 kg N/ha to 137 kg N/ha. As a precautionary approach, a reduction of 26 kg N/ha is assumed, based on the most geographically representative reference (Table 10).

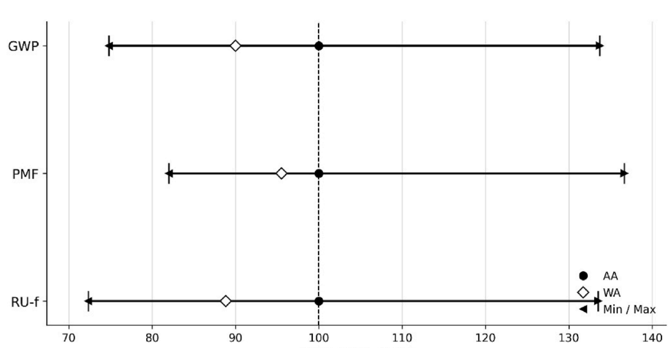

Fig. 3. Statistical representation of the variability of the three main impact indicators. Results are normalised by setting the arithmetic average (AA) of each impact category equal to 100. Horizontal bars represent the minimum–maximum range observed across the analysed companies, while markers indicate the arithmetic average (AA) and the production-weighted average (WA).

Table 7
Annual yield of sampled companies.

Annual yield of sample companies		
Minimum yield	5,51	tonSS/ha
Average yield (arithmetic)	7,57	tonSS/ha
Average yield (weighted)	7,83	tonSS/ha
Maximum yield	9,97	tonSS/ha
National average yield (2014–2020)	7,30	tonSS/ha

Table 8
Uptake in aboveground biomass.

CO_2 uptake in aboveground biomass		
Minimum yield	9,49	tonCO_2/ha
Average yield (arithmetic)	13,05	tonCO_2/ha
Average yield (weighted)	13,49	tonCO_2/ha
Maximum yield	17,18	tonCO_2/ha

Table 9
Uptake in belowground biomass.

CO_2 uptake in belowground biomass		
Minimum yield	3,04	tonCO_2/ha
Average yield (arithmetic)	4,18	tonCO_2/ha
Average yield (weighted)	4.32	tonCO_2/ha
Maximum yield	5,51	tonCO_2/ha

Table 10
"N-Credits": literature values by geographical area.

Residual nitrogen by N-fixing crops (kgN/ha)		
Po Valley, Italy	26	Tabacco and Comino (2016)
Michigan, USA	24	Harris and Hesterman (1990)
Ontario, Canada	143	Bruulsema and Christie (1987)
Manitoba, Canada	137	Kelner et al. (1997)
Utah, USA	112	Creech et al. (2020)

By applying the calculation model described in the materials and methods section, an estimated reduction in carbon footprint of 200,9 kg CO_2eq/ha is obtained for each hectare cultivated in rotation with alfalfa.

4. Discussion

4.1. Interpretation of LCIA results

The LCA results show that the production of dehydrated alfalfa forage has a non-negligible environmental impact, primarily driven by the artificial dehydration phase, which requires a considerable amount of thermal energy. Considering the climate change indicator, the drying stage accounts for approximately 45–50% of total GWP, while the cultivation phase contributes around 20–25%, and distribution adds a further 25–30%. Packaging represents only a minor share, about 1–3% of the total GWP. The drying process emerges as the key hotspot for climate impact. On average, it contributes roughly 130–140 kg CO_2eq per tonne, mainly due to the combustion of natural gas for heat generation. This highlights the energy intensity of the dehydration step and suggests that improvements in energy efficiency could substantially reduce the overall footprint. The cultivation phase has a relatively modest contribution, thanks largely to alfalfa's "low-input" nature. The lack of irrigation further decreases the environmental burden, as Italian alfalfa cultivation is rainfed. Nevertheless, the use of diesel fuel for multiple harvests remains a notable source of emissions. The distribution phase contributes significantly not only to GHG emissions but also to other environmental impact categories, particularly Particulate Matter Formation (PMF). Distribution accounts for about 70% of the total PM impact, mainly due to tailpipe emissions (NO_x and particulates) from diesel-powered trucks. The drying phase adds approximately 10–15%, and cultivation about 15%, while packaging remains negligible. These findings underscore that logistics, considered a downstream activity, also represent a meaningful lever for improving the sustainability of dehydrated forage, especially given the large volumes transported both by road and by sea. Proximity to local markets helps limit these impacts, but as trade expands, transport related emissions may grow. Beyond climate change and air quality impacts, the study also examined fossil resource use. Producing one tonne of dehydrated alfalfa requires approximately 3.500 MJ of primary fossil energy, equivalent to about 972 kWh. This total includes not only the direct consumption of natural gas, diesel, and electricity but also the embodied energy of upstream inputs. The stage-by-stage breakdown mirrors that of GWP: drying consumes about 45% of total fossil energy, cultivation 25%, distribution 26%, and packaging 1–2%. To further address this aspect, a variability analysis was performed by distinguishing between inter annual variability, referring to differences across the 2019–2023 period, and between firm variability, referring to differences among the surveyed companies, as proposed by (Thom et al., 2026). The variability analysis was conducted on four key foreground inventory flows associated with the cultivation and dehydration stages: diesel use for soil preparation and sowing, diesel use for cutting and collection, natural gas consumption for dehydration, and electricity consumption. These flows were selected because consistent multi-year and company-specific data were available for the sampled facilities. They should not be interpreted as the dominant contributors to all three priority impact categories, since the contribution analysis shows that distribution is the main contributor to Particulate Matter Formation. Fig. 4 shows the relative contribution of inter annual and between firm variability for these four flows. For diesel use related to soil preparation and sowing, variability is mainly driven by inter-annual differences, which account for 65% of the observed variability. This result can be explained by the distribution of alfalfa fields across different stages of the cultivation cycle, as soil preparation and sowing are mainly associated with the establishment phase of the crop. For diesel use related to cutting and collection, between-firm variability becomes more relevant, accounting for 64% of the observed variability. This reflects differences in harvesting technologies and machinery, as reported in section 2.1.3. In addition, one of the surveyed facilities operates in hilly areas, where field morphology can lead to higher fuel consumption during cutting and collection operations, increasing the variability observed for this inventory flow. For the industrial dehydration stage, variability is mainly associated with differences among companies. Natural gas consumption is strongly affected by between-firm variability, which accounts for 85% of the observed variability. Although annual variations in crop moisture content and yield can influence the amount of energy required for drying.

A similar pattern is observed for electricity consumption, for which between-firm variability accounts for 98% of the observed variability, while inter-annual variability plays only a marginal role. This suggests that electricity consumption is mainly determined by plant specific characteristics. Overall, the analysis shows that cultivation related flows

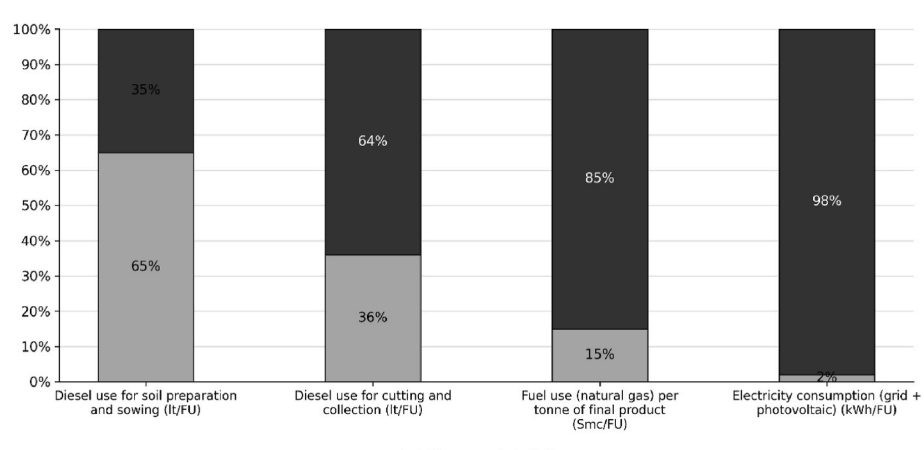

Fig. 4. Relative contribution of inter-annual and between-firm variability for four selected foreground inventory flows associated with the cultivation and dehydration stages. The bars show the percentage contribution of variance across years (2019–2023) and variability among the surveyed companies for diesel use in soil preparation and sowing, diesel use in cutting and collection, natural gas consumption for dehydration, and electricity consumption.

are influenced by both temporal and company specific factors, while energy consumption in the dehydration stage is predominantly driven by differences among facilities. This confirms the relevance of conducting a dedicated in depth analysis of energy consumption across AIFE associated companies. Such a project is currently being launched and is expected to start in 2026. The other LCIA indicators showed expected trends: acidification and eutrophication potentials from this system were relatively low, due to low fertilizer inputs. Terrestrial acidification potential was mainly driven by ammonia from the crop and NO_x from combustion, but since no nitrogen fertilizer is applied, the acidification per tonne of product was modest. Freshwater eutrophication was negligible, and marine eutrophication impacts were small given minimal nitrate leaching in perennial alfalfa fields. Water deprivation potential was extremely low for Italy's rainfed system (essentially only the water used in production of inputs). Ozone formation impacts were primarily from agricultural emissions and transport; again, transport dominated that category. Overall, none of these categories revealed additional hotspots beyond what the climate/energy analysis highlighted, reinforcing that energy use and fuel combustion are the primary drivers of environmental impact in the system. The land use impact category also deserves specific consideration. In the weighted average results, this category shows one of the highest impact, with a total value of 2.77E+03 Pt (points) per functional unit, mainly driven by the cultivation stage. In the EF 3.1 method, this category expresses the potential impact associated with land occupation and land transformation. Since land-use change is considered negligible because alfalfa is cultivated on existing agricultural land, the result is mainly related to land occupation (the area and the time of occupation of agricultural land required to produce the functional unit). However, this impact category does not fully capture the agronomic role that perennial alfalfa that is introduced between annual crops to provide a multi-year break period, contributing to soil cover, reduced soil disturbance, improved soil structure, and the restoration of soil fertility through biological nitrogen fixation. For this reason land use result should be interpreted together with the agronomic function of alfalfa.

4.2. *Interpretation of other environmental indicators results*

Regarding carbon uptake in above-ground biomass, very high values are observed, which largely offset the amount of emissions generated throughout the supply chain. However, it is essential to evaluate these uptakes from a life cycle perspective, rather than limiting the assessment to a cradle-to-gate approach. The carbon stored in the harvested biomass cannot be considered a long-term sequestration, as it is released back into the atmosphere over a relatively short time frame through downstream processes. This interpretation aligns with the technical principles of LCA and with European regulations on carbon sequestration, which require compliance with the QU.A.L.ITY criteria, specifically the long-term permanence of the sequestration (European Commission, 2022). In this context, that condition is not met. Nevertheless, within a life cycle framework, it remains important to account for these carbon uptakes, particularly when assessing the environmental impacts of agricultural products within broader value chains, such as milk production. In most cases, these absorption contributions are neglected or assumed to be zero, both due to the absence of specific regulatory guidance and to avoid the complexity of modeling biological processes such as human digestion, as foreseen, for example, in the PEF rules for milk and meat (European Dairy Association, 2019; European Livestock and Meat Trades Union, n.d.). The PEF Product Category Rules (PCRs) recommend reporting such values separately under "Additional Technical Information" (European Commission, 2018). It should also be recognized that a significant portion of agricultural product emissions arises from biogenic sources, especially enteric fermentation, which produces methane originating from carbon previously absorbed during upstream cultivation. Therefore, an approach that considers only emissions, without acknowledging biogenic carbon uptake, may be precautionary, yet potentially misleading. While it is true that absorbed carbon is partly converted into methane, which has a higher GWP than CO_2, completely disregarding these biogenic flows ultimately reduces the accuracy and representativeness of the LCA results. Aboveground biomass uptake is reported only as additional technical information and must not used to offset, reduce, or net against the cradle-to-gate GWP result of 243 kg CO_2eq/t.

From the perspective of belowground biomass carbon, the estimated values are significantly lower than those calculated for aboveground biomass. However, these values should be interpreted with caution. The estimate reported in this study refers to carbon contained in belowground root biomass and should not be considered equivalent to a net increase in soil organic carbon stock. Although the root system remains in the soil after harvest and may contribute to soil organic matter formation, the proportion of root-derived carbon that is effectively stabilised in the soil depends on several factors, including soil properties, climatic conditions, microbial activity, crop management, rotation length, and the time horizon considered (Lal, 2004). Therefore, belowground biomass carbon is conceptually different from a net soil organic carbon increment attributable to alfalfa cultivation. The latter is the quantity that would be relevant for assessing carbon removal or sequestration claims under emerging European carbon removal frameworks and would require direct SOC measurements over time, comparison with an appropriate baseline, and verification of permanence (European Commission, 2022). In the present study, no direct SOC measurements were available for the sampled fields. Consequently, the belowground biomass estimate, as already stated, is reported only as additional technical information and should not be interpreted as a measured SOC increase, a permanent carbon removal, or a sequestration credit. To accurately determine how much carbon from root biomass is effectively retained in the soil, while avoiding the risk of double counting, the approach would be the direct measurement of soil organic carbon stocks and the analysis of their temporal variations. However, direct SOC monitoring was outside the scope of the present study and may also present practical limitations in terms of cost and applicability at the level of individual companies. Regarding the climate change benefit resulting from the avoided use of synthetic fertilizers, the value reported in the results section represents the quantified environmental benefit associated with fertilizer avoidance, a potential source of nitrogen, and was obtained through a calculation model based on estimations. This value refers to a specific application scenario, namely the rotation of alfalfa with other crops, and was calculated using the currently available methodologies. The estimate considers a four-year period, corresponding to the typical lifespan of an alfalfa stand. Therefore, to obtain an annual benefit per hectare, the value should be divided by four, assuming that the generation of nitrogen credits occurs linearly over time. It should be noted that this is a model-based estimate, intended to provide an order of magnitude for the potential benefit, and that it does not represent a significant impact when compared to the total production-related emissions.

4.3. *Improvement opportunities*

The LCA results highlight that the energy demand for dehydration is the main factor influencing the environmental impact of dehydrated forage. Converting a moist green crop into a stable dry feed requires substantial energy, which is typically supplied by fossil fuels. In the Italian context analysed, natural gas combustion was responsible for nearly half of the total GHG emissions. This finding suggests that strategies to reduce the carbon footprint of dehydrated alfalfa should primarily target the drying phase, either by improving energy efficiency or by switching to cleaner energy sources. Some Italian facilities have already integrated solar photovoltaic systems to offset part of their electricity demand, achieving a 10%–20% reduction in grid energy consumption. The total electricity consumption of the companies sampled is substantial, ranging from approximately 1000 to 6000 MWh per year. Under these conditions, photovoltaic (PV) systems represent not only an environmental measure but also an economic lever for competitiveness, as they reduce companies' exposure to electricity market volatility. This aspect is particularly relevant in the Italian context, where electricity prices have shown significant and unpredictable fluctuations, as reflected by the National Single Price (PUN). At the same time, the investment cost of photovoltaic systems has decreased to below 1000 € per kWp, while average annual electricity yields in northern Italy exceed 1200 kWh per kWp. Within this framework, the average payback period for PV installations in companies with comparable electricity consumption profiles is estimated to range between 3 and 4 years, making such investments highly economically attractive. From an environmental perspective, adopting a location-based approach and considering the Italian residual electricity mix, the implementation of on-site photovoltaic generation allows for the reduction of Scope 2 greenhouse gas emissions by 414.9 g CO_{2eq} per kWh of electricity substituted (ISPRA, 2025). Another potential improvement option involves the use of biomass-fueled dryers. Although these systems may introduce technical and economic constraints, they could reduce fossil-based greenhouse gas emissions by replacing natural gas with a renewable energy carrier whose direct combustion emissions are predominantly biogenic. To provide a quantitative indication of this potential effect, a comparative modelling framework was developed to estimate the Global Warming Potential (GWP) associated with heat generation from natural gas and biomass during the dehydration process. The functional unit was kept consistent with the LCA study, namely 1 tonne of finished dehydrated alfalfa, and the comparison assumes that both fuels supply the same useful heat demand. The assessment is limited to the thermal-energy generation stage of the industrial dehydration process. The biomass substitution assessment was developed as an illustrative screening calculation rather than as a full LCA scenario analysis. Its purpose is to provide an order-of-magnitude estimate of the potential change in climate-related emissions associated with replacing natural gas with biomass for heat generation during dehydration. Therefore, the calculation should not be interpreted as a comprehensive comparison of the environmental performance of natural gas and biomass supply chains. Potential burden shifting to other life-cycle stages or environmental impact categories was not assessed and would require a dedicated comparative LCA. DEFRA emission factors were used for this screening calculation because they provide a single, transparent and methodologically documented source of greenhouse gas conversion factors for different fuels, including direct combustion emissions, upstream supply-chain contributions and the separate reporting of biogenic CO_2 emissions (United Kingdom Department for Enviroment, Food and Rural Affairs (DEFRA), Department for Energy Security and Net Zero, 2024). The model assumes an identical useful thermal demand per tonne of product for both energy supply options, while accounting for differences in boiler efficiency and upstream emission profiles. Natural gas consumption was derived from measured operational data and corresponds to 25.15 Smc per tonne of finished product, equivalent to 913 MJ of useful thermal energy per tonne, assuming a lower heating value of 36.3 MJ per Smc.

$$Q_{use} = V_{gas} \cdot LHV_{gas} \cdot \eta_{gas}$$

Equation 5. Estimation of useful thermal energy per tonne.

V_{gas} = *natural gas consumption* $(Sm^3/ton\ FU)$

LHV_{gas} = *lower heating value of natural gas* (MJ/Sm^3)

η_{gas} = *efficiency of the gas boiler*

$$E_{fuel,gas} = \frac{Q_{use}}{\eta_{gas}}$$

Equation 6. Natural gas energy demand for heat generation.

For the biomass-based option, an average mix of chips, logs and pellet were considered as fuel, with representative efficiency values assumed for industrial biomass boilers. Fuel properties were gained by DEFRA tables.

$$E_{fuel,biomass} = \frac{Q_{use}}{\eta_{biomass}}$$

Equation 7. Biomass energy demand for heat generation.

$\eta_{biomass}$ = *biomass boiler efficiency*

Also greenhouse gas emissions were calculated adopting emission factors from the DEFRA database. Fossil GWP includes upstream emissions and combustion-related non-CO_2 gases, while biogenic CO_2 emissions from biomass combustion were quantified and reported separately. For natural gas combustion, the DEFRA factor used in this scenario is substantially consistent with the Italian national standard parameter used for EU ETS reporting, equal to 0.056212 kg CO_2/MJ. However, the remaining biomass-related factors are not Italy-specific and were retained for consistency and practicality, avoiding the combination of heterogeneous factors from multiple sources.

$$GWP_{fossil,gas} = E_{fuel,gas} \cdot (EF_{up,gas} + EF_{comb,gas})$$

Equation 8. Calculation of fossil GWP associated with natural gas heat generation.

$$GWP_{fossil,biomass} = E_{fuel,biomass} \cdot (EF_{up,biomass} + EF_{comb,biomass})$$

Equation 9. Calculation of fossil GWP associated with biomass heat generation.

$$GWP_{biogenic,biomass} = E_{fuel,biomass} \cdot EF_{biogenic,comb,biomass}$$

Equation 10. Calculation of biogenic GWP associated with biomass combustion.

$EF_{up,gas}$ = *upstream emission factor for natural gas* $(kg\ CO_2eq/MJ)$

$EF_{comb,gas}$ = *combustion emission factor for natural gas* $(kg\ CO_2eq/MJ)$

$EF_{up,biomass}$ = *upstream emission factor for biomass* $(kg\ CO_2eq/MJ)$

$EF_{comb,biomass}$ = *non* CO_2 *emissions from biomass combustion* $(kg\ CO_2eq/MJ)$

$EF_{biogenic,comb,biomass}$ = *biogenic* CO_2 *emissions from biomass combustion* $(kg\ CO_2eq/MJ)$

By comparing the climate change impact indicators, the effect of biomass use in terms of greenhouse gas emission reduction can be assessed (Equation 11–12).

$$\Delta GWP_{fossil} = GWP_{fossil,biomass} - GWP_{fossil,gas}$$

Equation 11. Change in fossil GWP resulting from biomass substitution.

$$\Delta GWP_{biogenic} = GWP_{biogenic,biomass}$$

Equation 12. Additional biogenic GWP emissions resulting from biomass substitution.

Using a simplified comparison based on calorific values and DEFRA average emission factors, a reduction in fossil carbon footprint of approximately 60 kg CO_2eq per tonne of finished product can be estimated. When compared with the reference impact of 109 kg CO_2eq (WA, GWPf, Table 4), this corresponds to an overall reduction of about 44%. However, this substitution leads to a substantial increase in biogenic CO_2 emissions, amounting to approximately 111 kg CO_2eq per tonne of finished product (Table 11).

A further opportunity lies in the recovery and reuse of waste heat. Since alfalfa dehydration typically requires a controlled airflow at temperatures below 100°C, low-temperature waste heat from nearby industrial processes could potentially be harnessed. Developing "industrial symbioses" would again demand a thorough techno-economic feasibility assessment and collaborative partnerships between sectors. With regard to energy management, one of the most important yet still underdeveloped improvement areas in the sector is the digitalization of energy consumption. The installation of dedicated meters for electricity

Table 11
Simulation of the potential Climate Change effect of replacing natural gas with a biomass fueled boiler for the dehydration process. Results are expressed per functional unit (FU), defined as 1 ton of finished dehydrated alfalfa, and distinguish between fossil GWP and biogenic CO_2 emissions.

Indicator	Value	Unit of measure
Useful heat demand, Q_{use}	913	MJ/tonne (FU)
Gas boiler efficiency, η_{gas}	0.90	%
Biomass boiler efficiency, $\eta_{biomass}$	0.80	%
Gas upstream emission factor, $EF_{up,gas}$	0.009	$kgCO_2eq/MJ$
Gas combustion emission factor, $EF_{comb,gas}$	0.056	$kgCO_2eq/MJ$
Biomass upstream emission factor, $EF_{up,biomass}$	0.002	$kgCO_2eq/MJ$
Biomass non-CO_2 emission factor, $EF_{comb,biomass}$	0.003	$kgCO_2eq/MJ$
Biomass biogenic CO_2 emission factor, $EF_{biog.,comb,biom.}$	0.097	$kgCO_2eq/MJ$
Fossil GWP, gas, $GWP_{fossil,gas}$	66.5	$kgCO_2eq$/tonne (FU)
Fossil GWP, biomass, $GWP_{fossil,biomass}$	6.1	$kgCO_2eq$/tonne (FU)
Biogenic CO_2, biomass, $GWP_{biogenic,biomass}$	111.0	$kgCO_2$/tonne (FU)
Fossil GWP difference, ΔGWP_{fossil}	−60.4	$kgCO_2eq$/tonne (FU)

and thermal energy enables the quantification of process-level energy use and its daily monitoring. This approach supports the identification of operational inefficiencies, abnormal consumption patterns and optimization opportunities, while also improving the quality and reliability of the data used for environmental assessments. Among the five companies analysed, only two had a dedicated system for the detailed monitoring of energy consumption, while one of them was in the process of installing such a system at the time of data collection. This study's integrated life cycle perspective enables a broader discussion of net sustainability. On one hand, the dehydration process emits CO_2 and consumes energy, an environmental cost that trades off against the benefit of producing a high-quality, storable feed. On the other hand, alfalfa cultivation provides important soil and ecosystem services, such as nitrogen fixation and organic carbon accumulation. The present work aims to move in this direction by quantifying both burdens and potential benefits. At this stage, the quantification of emissions is well established, supported by a defined methodology and third-party verification. Conversely, the estimation of benefits, such as avoided fertilizer use or carbon uptake, relies primarily on bibliographic data and modeling approaches. Further research is needed to integrate these models with field data and direct measurements, as already initiated in other applied studies such as the MediCarbonio project (Centro Ricerche Produzioni Animali - CRPA and Filiera Italiana Foraggi - AIFE, 2021). This represents the next essential step toward a more comprehensive and evidence-based understanding of alfalfa's role in sustainable forage production.

5. Conclusion

This study provides a detailed assessment of the environmental impacts associated with the production of dehydrated alfalfa forage in Italy, while also exploring the agronomic and environmental co-benefits of alfalfa cultivation. The LCA results indicate that dehydrated alfalfa has a production-weighted average carbon footprint of 243 kg CO_2eq per tonne of finished product, calculated across the five surveyed plants over the five-year reference period. The dehydration stage is the dominant contributor to climate change and fossil resource use, mainly due to the consumption of natural gas and energy required for the drying process, making it the primary target for mitigation through energy efficiency improvements and the adoption of cleaner energy sources. Particulate matter formation, on the other hand, is mainly influenced by distribution and transport related emissions, highlighting the relevance of logistics optimization in addition to process-level energy improvements. The proposed carbon footprint value should be interpreted together with the variability observed among the surveyed facilities. As discussed in the Results section, the analysis showed a non-negligible variability across companies, particularly for the most relevant stage, namely industrial dehydration. This indicates that differences in plant configuration, energy efficiency, process management, and monitoring systems can significantly influence the environmental performance of dehydrated alfalfa production. For this reason, a dedicated follow up project has been launched to further investigate energy consumption across the companies involved in this study and additional AIFE associated plants, with an enlarged sample focused specifically on the dehydration stage. This future work will allow a more detailed understanding of the causes of variability among facilities, support the identification of plant level improvement opportunities, and assess the granularity and effectiveness of existing energy monitoring and control systems. Beyond its processing impacts, the cultivation of alfalfa could offer environmental co-benefits, including enhanced soil health and organic carbon content, as well as a reduced need for synthetic fertilizers thanks to biological nitrogen fixation. Although these benefits lie outside the conventional LCA boundaries, they could significantly improve the overall sustainability profile of alfalfa and generate positive effects for subsequent crops and the broader agroecosystem. From a holistic sustainability perspective, dehydrated alfalfa can be regarded as a product that entails certain processing-related environmental costs but simultaneously delivers agronomic and ecological advantages at the farm level. Although the LCA results are robust and have been independently verified, enabling AIFE's ISO 14044 certification, there remains room for improvement in primary data collection, particularly regarding electricity consumption at the facility level and transport-related data for raw material delivery. Additionally, future research should include field experiments aimed at quantifying soil carbon dynamics under alfalfa cultivation in Italy, to strengthen the current estimates of carbon sequestration and further refine the understanding of alfalfa's role within sustainable agricultural systems.

CRediT authorship contribution statement

Valentino Solfrini: Conceptualization, Data curation, Formal analysis, Writing – original draft. **Augusto Bianchini:** Methodology, Project administration, Supervision. **Daniele Duca:** Validation, Writing – review & editing. **Ivan Savini:** Data curation, Writing – original draft.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with translation from Italian into academic English, formatting and stylistic standardization of figures. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the published article.

Declaration of competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Augusto Bianchini reports a relationship with AIFE - Associazione Italiana Foraggi that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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