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Quantification of Mechanical Dry Matter Losses During Lucerne (*Medicago sativa* L.) Hay Harvesting under Arid Conditions in Laghouat Province, Algeria

Mourad Hattab[1*], Ibrahim Sifi[2], Hicham Gouzi[3]

[1]Department of Agronomic Sciences, Faculty of Sciences, Laboratory of Biological and Agronomic Sciences (LSBA), University of Amar Telidji, Laghouat, Algeria

[2]Department of Biological Sciences, Faculty of Sciences, Fundamental Sciences Laboratory, University of Amar Telidji, Laghouat, Algeria

[3]Department of Biological Sciences, Faculty of Sciences, Laboratory of Biological and Agronomic Sciences (LSBA), University of Amar Telidji, Laghouat, Algeria

[*]Corresponding author. E-mail: m.hattab@lagh-univ.dz

ABSTRACT

Mechanical dry matter losses during lucerne (*Medicago sativa* L.) hay harvesting represent a major constraint on forage production efficiency in arid regions, yet remain poorly quantified under such conditions. This study aimed to quantify and analyse mechanical losses throughout the complete harvest chain (mowing, raking, and baling) of lucerne hay under arid conditions in the Laghouat region, Algeria. Five fields differing in cultivar, stand age, seeding rate, and cutting stage were monitored during the first cut of spring 2025. Initial dry matter yield (DMYi) was assessed through pre-harvest plot sampling, whilst harvested yield (DMYh) was determined by bale weighing and corrected for weed content. Respiration and leaching losses were estimated using established empirical models, based on MERRA-2 satellite-derived climate data corrected for local conditions. Fresh matter yield showed no significant between-field differences ($p = 0.26$), whereas DMYi varied significantly ($p = 0.014$), ranging from 4.96 to 6.94 $t \cdot ha^{-1}$. Total mechanical losses (TML) ranged from 18.1% to 49.0% of DMYi, with an overall mean of 31.24%, substantially exceeding internationally accepted thresholds (8-21%). Weed infestation (up to 16.19%) and unfavourable drying conditions, including leaching losses of up to 15%, were identified as critical loss drivers. These findings highlight the urgent need to improve harvest chain management in arid forage systems through optimised operation timing, effective weed control, and the adoption of better-adapted harvesting equipment.

Keywords: lucerne, hay harvesting, mechanical losses, dry matter, arid conditions.

INTRODUCTION

Lucerne (*Medicago sativa* L.) is one of the most widely cultivated perennial forage legumes in the world, valued for its superior nutritional composition (18-25% crude protein) and remarkable adaptability across diverse pedoclimatic environments (Frame et al., 1998; Putnam et al., 2007). Its deep root system, nitrogen-fixing capacity, and high biomass productivity make it a crop of strategic importance in regions where animal feed resources are scarce and climatic constraints are severe. Within the arid and semi-arid zones of North Africa, characterised by annual precipitation below 400 mm and pronounced seasonal water deficits, lucerne cultivation plays a critical role in sustaining livestock feed security and maintaining the ecological viability of agropastoral production systems.

In Algeria, where arable land is limited to approximately 3.6% of the total territory and the climate is predominantly arid Mediterranean, forage production faces multiple and interconnected constraints (MADR, 2021). The scarcity and irregular distribution of rainfall, combined with high evapotranspiration rates and degraded range resources, severely limit the supply of quality roughage for livestock. Under these conditions, purchasing dry forage on the market remains prohibitively costly for most smallholder livestock producers, further deepening the structural feed deficit (Abdelguerfi and Laouar, 1999; Hadj Omar et al., 2018). These challenges highlight the urgency of optimising the entire forage production chain, from crop

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establishment through to harvest and conservation, in order to maximise the recovery of the biomass produced.

Harvest losses represent a critical and often underestimated bottleneck in forage valorisation. Under temperate conditions, dry matter losses during haymaking operations have been estimated at an average of 16% (Koegel et al., 1985). However, reference values established in climatically favourable environments may substantially underestimate the magnitude of losses occurring under arid conditions, where the combination of extreme temperatures, low relative humidity, and logistical constraints can markedly amplify mechanical fragmentation and leaf shatter. In the Laghouat region, the lucerne hay harvest chain comprises three successive operations - mowing, raking, and baling - each of which constitutes a specific risk point for dry matter loss, particularly given the brittleness of dried lucerne leaves at elevated temperatures.

Beyond their quantitative dimension, mechanical losses carry significant nutritional consequences. The marked difference in crude protein content between lucerne leaves and stems (Milic et al., 2011; Okumus et al., 2021) means that any preferential loss of leaf material during harvesting operations results in a disproportionate reduction in the protein value of the recovered hay, thereby compromising its zootechnical efficacy and economic value for livestock producers.

Despite its agronomic and economic significance, the quantification of mechanical losses during lucerne hay harvesting under arid conditions remains poorly documented in the scientific literature, particularly in the Algerian context. The present study aims to address this knowledge gap by quantifying and analysing mechanical dry matter losses throughout the complete harvest chain in Laghouat province, Algeria. The specific objectives are: (i) to quantify total mechanical losses and their principal components; (ii) to identify the agronomic and climatic factors determining these losses; and (iii) to propose improvement strategies adapted to local constraints.

MATERIAL AND METHODS

Study Region and Environmental Conditions

The study was conducted in the municipality of Ben Nacer Benchohra, Laghouat province, located in southern Algeria. This arid region has a dry climate characterised by annual rainfall below 200 mm, summer temperatures exceeding 40°C, and high evapotranspiration. The soils are predominantly sandy-loam with low organic matter content. This area constitutes a representative environment for forage cropping systems under arid conditions, where lucerne (*Medicago sativa* L.) is the main perennial crop intended for hay production (Hattab et al., 2025).

Experimental Site and Cultural Conditions

The experiment was carried out in spring 2025 on five lucerne fields distributed throughout the study municipality. The first annual cut was performed during April under comparable meteorological conditions between sites. The fields were managed under an extensive system, without chemical inputs, with regular irrigation provided by manually displaced sprinkler systems (2 to 3 irrigations per week). The five lucerne fields differed notably in terms of area, variety grown, stand age, seeding rate, grazing history, and cutting stage (Table 1). These characteristics contributed to the observed variability in mechanical dry matter losses between sites.

Table 1. Main agronomic and cultural characteristics of the studied fields

Field	Area (ha)	Variety	Age (years)	Seeding rate ($kg \cdot ha^{-1}$)	Grazing before cutting	Cutting stage
1	0.6	Speed	1	60	No	Budding
2	1.4	CUF 101	2	50	Yes	Early flowering
3	2.5	CUF 101	6	40	Yes	Early flowering
4	3.8	Speed	4	40	No	Early flowering
5	2.0	CUF 101	3	40	Yes	Budding

Harvest Process and Operations Chronology

The lucerne hay harvest chain in this region comprises three main stages:

- **Cutting**: performed with a rotary drum mower;
- **Raking**: carried out using a single-rotor rake;
- **Baling**: performed with a small rectangular baler.

The precise timing of each operation was recorded to assess its potential influence on mechanical losses and hay quality. The drying duration before baling varied from 5 to 8 days according to local climatic conditions (temperature, precipitation).

Assessment of Initial Dry Matter Yield (DMYi)

Field Sampling: Two to three days before harvest, eight 1 m^2 plots were randomly demarcated in each field and manually mown at the cutting height used by farmers (5-6 cm). The harvested fresh matter was immediately weighed using a portable digital scale (precision ± 5 g) and then packed in plastic bags. The fresh matter yield (FMY) ($t{\cdot}ha^{-1}$) was calculated according to the following equation:

$$\text{FMY}\ (\text{t}\cdot\text{ha}^{-1}) = \frac{\sum \text{FM weight per plot (t)}}{8} \times 10000$$

Determination of Dry Matter Content: A composite sample of 2 kg was constituted by collecting 250 g from each of the eight plots. This composite sample was air-dried for 7 days under conditions similar to natural field drying. After drying, the residual dry matter was manually separated into leaf and stem fractions. The proportion of each fraction was determined by individual weighing, allowing calculation of the leaf-to-stem ratio as an indicator of hay nutritional quality. The initial dry matter yield (DMYi) was obtained by summing the residual dry matter and the estimated respiration losses.

Assessment of Harvested Yield

Weighing of Bales: On the day of baling, 30 bales were randomly selected from each field and individually weighed using a digital balance. The mean bale weight was calculated as the arithmetic mean of these 30 measurements.

Correction for Weed Content: Using a cylindrical metal probe with a toothed end, a composite dry matter sample was collected from 10 bales harvested in each field. Weeds were manually sorted and weighed separately. The weed proportion (%) was calculated using the following equation:

$$\text{Weed proportion (\%)} = \frac{\text{Weight of weeds}}{\text{Initial total weight of the composite sample}} \times 100$$

The corrected mean bale weight, excluding weed content, was determined using the following equation:

$$\text{Corrected mean bale weight (kg)} = \text{Mean bale weight (kg)} \times \left(1 - \frac{\text{Weed proportion}}{100}\right)$$

The harvested dry matter yield (DMYh) ($t{\cdot}ha^{-1}$) was obtained as the product of the number of bales per hectare and the corrected mean bale weight.

Calculation of Total Mechanical Losses (TML)

Total mechanical losses were determined by difference between the initial dry matter and that actually harvested, after deducting respiration and leaching losses:

$$\text{Total Mechanical Losses (TML) (\%)} = \text{Initial DM} - (\text{Harvested DM} + \text{Oxidised DM} + \text{Leached DM})$$

Estimation of Respiration Losses: The proportion of dry matter oxidised through respiration was estimated according to Honig (1980), as a function of temperature and water content of the forage during the drying period (Figure 1).

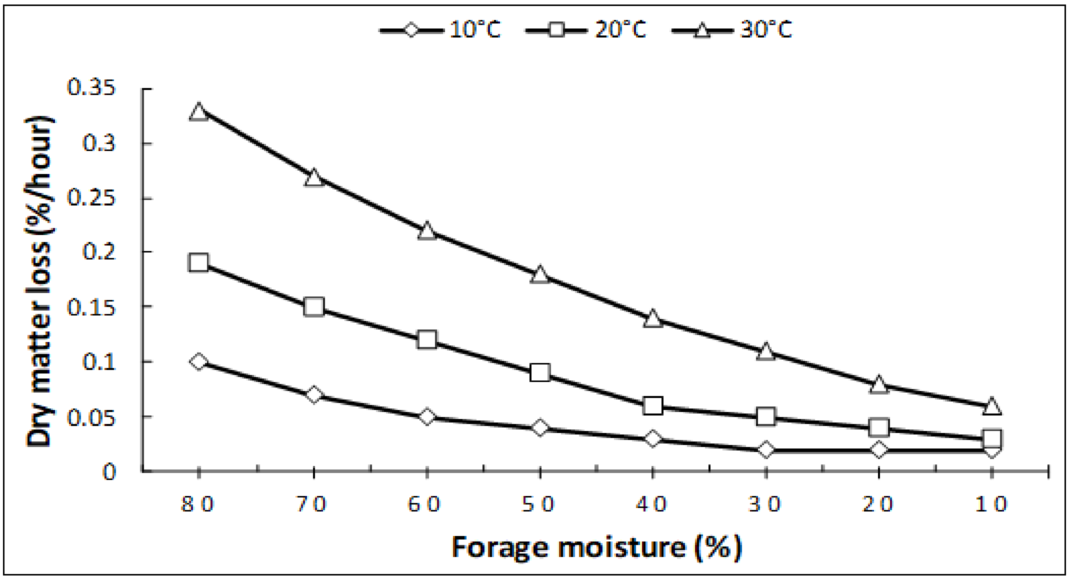

Figure 1. Dry matter losses through respiration as a function of temperature and forage moisture content (Honig, 1980)

Estimation of Leaching Losses: In the event of precipitation, leaching losses were estimated according to Rotz and Muck (1994), Savoie cited by Piette (2002), and Rotz (2005), with rates ranging from 5% to more than 20% depending on precipitation intensity.

Figure 2 illustrates the daily variations in temperature and precipitation for April 2025. In the absence of a local meteorological station, we used MERRA-2 satellite climate data, previously corrected using the correction formulae developed by Khoudiri et al. (2025). These climatic variables served as the basis for estimating dry matter losses through respiration and leaching, taking into account the drying duration specific to each field.

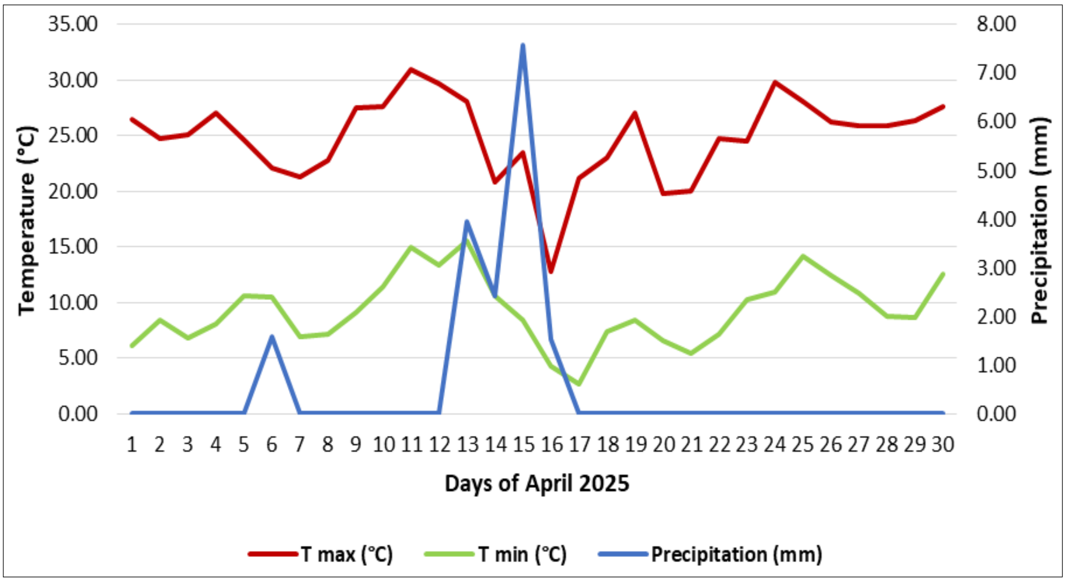

Figure 2. Daily precipitation and minimum and maximum temperatures for April 2025

Statistical Analysis

The data were subjected to descriptive and inferential statistical analyses using XLSTAT software (version 2025.1.0). For each quantitative variable, measures of central tendency (arithmetic mean) and dispersion (standard deviation) were calculated. Differences between field means were assessed by one-way analysis of variance (ANOVA), followed by Tukey's HSD multiple comparison test where significant differences were detected (α = 0.05). Results are presented as means ± standard deviations and coefficients of variation, accompanied by the corresponding probability values (*p*-values).

RESULTS AND DISCUSSION

Harvest and Forage Drying Conditions

The harvest conditions (timing of different operations) and forage drying duration are presented in Table 2. Drying duration varied from 5 to 8 days depending on the field, in relation to local climatic conditions. Field 3, where drying was prolonged over 8 days, coincided with several rainfall episodes, unlike fields 4 and 5, where drying was shorter (5-6 days). These durations were incorporated into the calculation of dry matter oxidation losses through respiration and, where rainfall occurred during drying, into the estimation of leaching losses.

Table 2. Harvest and forage drying conditions in the studied fields

Field	Mowing	Raking	Raking-baling interval	Baling	Drying duration (days)	Drying period (April 2025)
1	09h00	10h30	1 day	11h00	6	03-08 April
2	09h00	10h00	1 day	13h00	5	02-06 April
3	09h30	11h00	1 day	12h00	8	12-19 April
4	09h00	10h00	1 day	10h30	5	23-27 April
5	09h00	09h00	2 days	10h00	6	24-29 April

Fresh Matter Yield, Respiration and Leaching Losses

Fresh Matter Yield (FMY) showed moderate variability between fields, ranging from 18.16 ± 2.72 $t \cdot ha^{-1}$ (Field 5) to 22.48 ± 5.20 $t \cdot ha^{-1}$ (Field 2), with an overall mean of 20.59 ± 4.04 $t \cdot ha^{-1}$ (Table 3). Field 2 recorded the highest production, whilst Field 5 recorded the lowest yield. The analysis of variance (ANOVA) did not reveal statistically significant differences between fields for FMY [$F(4, 35) = 1.37$; $p = 0.26$], indicating relative homogeneity in primary production despite the diversity of cultural characteristics.

Oxidation losses varied from 9.54% (Field 2) to 13.53% (Field 3), reflecting the combined influence of drying duration and thermo-pluviometric conditions. Leaching losses affected only Fields 1, 2, and 3, with the greatest impact on Field 3 (15%) owing to four consecutive rainy days. Fields 4 and 5, which experienced dry conditions throughout drying, incurred no leaching losses.

Table 3. Fresh matter yield and rate of oxidised and leached dry matter

Field	FMY ($t \cdot ha^{-1}$)	CV (%)	DM oxidised in laboratory (%)	DM oxidised in field (%)	Number of rainy days	DM leached (%)
1	21.84 ± 2.65a	12.13	10.86	10.14	1	2
2	22.48 ± 5.20a	23.13	10.86	09.54	1	2
3	20.82 ± 4.96a	23.82	14.55	13.53	4	15
4	19.63 ± 4.68a	23.84	11.13	10.98	0	0
5	18.16 ± 2.72a	14.98	12.12	12.81	0	0
Mean	20.59 ± 4.04	19.62	11.90	11.40	-	3.80
ANOVA (p)	0.26^{ns}	-	-	-	-	-

FMY: Fresh Matter Yield; DM: Dry Matter; CV: Coefficient of Variation; ANOVA: Analysis of Variance; ns = not significant ($p \geq 0.05$).
Superscript letters indicate homogeneous groups according to Tukey's test (HSD) at 5% threshold.

Initial Dry Matter Yield

Initial dry matter yield (DMYi) ranged from 4.96 ± 0.74 t·ha^{-1} (Field 5) to 6.94 ± 1.60 t·ha^{-1} (Field 2), with an overall mean of 5.90 ± 1.18 t·ha^{-1} (Table 4). This variability reflects differences in agronomic characteristics between experimental sites. ANOVA revealed a significant field effect [$F(4, 35) = 3.62$; $p = 0.014$]. Tukey's post-hoc analysis indicated that the yield of Field 2 was significantly higher than that of Field 5 ($p = 0.026$), whilst all other pairwise comparisons were non-significant ($p \geq 0.05$). Morphological composition also contributed to this variability: Field 5, with a high leaf proportion (51.2% of DM), exhibited better nutritive value, whereas Field 1, with a higher stem proportion, produced more fibrous forage.

Table 4. Initial DM yield and associated parameters for the studied fields

Field	Residual DMY (t·ha^{-1})	CV (%)	% (Residual DM/FM)	% LDM	% SDM	(LDM/SDM) ratio	% DM oxidised	DMYi (t·ha^{-1})	CV (%)
1	4.70 ± 0.57ab	12.13	21.5	37.2	62.8	0.59	10.86	5.27 ± 0.64ab	12.14
2	6.18 ± 1.43a	23.14	27.5	42.6	57.4	0.74	10.86	6.94 ± 1.60a	23.05
3	5.62 ± 1.34ab	23.84	27	42.6	57.4	0.74	14.55	6.58 ± 1.57ab	23.86
4	5.10 ± 1.22ab	23.92	26	44.23	55.77	0.79	11.13	5.74 ± 1.37ab	23.87
5	4.36 ± 0.65b	14.91	24	51.16	48.84	1.05	12.12	4.96 ± 0.74b	14.92
Mean	5.19 ± 1.04	20.04	25.20	43.56	56.44	0.78	11.90	5.90 ± 1.18	20.00
ANOVA (p)	0.017*	-	-	-	-	-	-	0.014*	-

DM: Dry Matter; FM: Fresh Matter; DMY: Dry Matter Yield; FM: Fresh Matter; LMD: Leaf Dry Matter; SMD: Stem Dry Matter; DMYi: Initial Dry Matter Yield; ANOVA: Analysis of Variance; CV: Coefficient of Variation; * = significant ($p < 0.05$).
Superscript letters indicate homogeneous groups according to Tukey's test (HSD) at 5% threshold.

Harvested Dry Matter Yield (DMYh)

The harvested yield ranged from 2.30 ± 0.30 t·ha^{-1} (Field 4) to 3.73 ± 0.34 t·ha^{-1} (Field 2), with an overall mean of 3.12 ± 0.34 t·ha^{-1} (Table 5). Fields 1 and 2 achieved the best recovery performance, whilst Field 4 recorded the lowest value.

ANOVA revealed a highly significant field effect on harvested yield [$F(4, 145) = 85.56$; $p < 0.0001$], reflecting the influence of varietal characteristics, stand age, and cultural practices on lucerne productivity. Tukey's post hoc analysis confirmed significant differences between fields for DMYh. Fields 1 and 2 (3.68 and 3.73 t·ha^{-1}, respectively), formed a homogeneous group with the highest values. Fields 3 and 5 (2.94 and 2.95 t·ha^{-1}) constituted an intermediate group, whilst Field 4 (2.30 t·ha^{-1}) was clearly distinguished as the lowest-yielding field. Figure 3 illustrates the progression of yields from primary production through to the effective harvest of lucerne hay.

Table 5. Harvested DM yield and associated quality parameters

Field	Mean bale weight (kg)	CV (%)	Composite sample (g)	Weight of weeds (g)	% (Weeds/ Composite sample)	Corrected mean bale weight (kg)	CV (%)	Number of bales·ha^{-1}	DMYh (t·ha^{-1})	CV (%)
1	17.85 ± 1.29b	07.23	515	10	01.94	17.50 ± 1.26b	07.20	210	3.68 ± 0.27a	07.34
2	20.90 ± 1.89a	09.04	610	05	00.82	20.73 ± 1.87a	09.02	180	3.73 ± 0.34a	09.11
3	22.28 ± 3.98a	17.86	515	40	07.77	20.55 ± 3.67a	17.86	143	2.94 ± 0.53b	18.03
4	19.60 ± 2.57b	13.11	525	85	16.19	16.43 ± 2.16c	13.15	140	2.30 ± 0.30c	13.04
5	18.48 ± 1.67b	09.04	475	10	02.11	18.09 ± 1.63b	09.01	163	2.95 ± 0.27b	09.15
Mean	19.82 ± 2.28	11.50	528	30	05.77	18.66 ± 2.12	11.36	167.20	3.12 ± 0.34	10.90
ANOVA (p)	< 0.0001***	-	-	-	-	< 0.0001***	-	-	< 0.0001***	-

DMYh: Harvested Dry Matter Yield; ANOVA: Analysis of Variance; CV: coefficient of variation; *** = highly significant ($p < 0.001$).
Superscript letters indicate homogeneous groups according to Tukey's test (HSD) at 5% threshold.

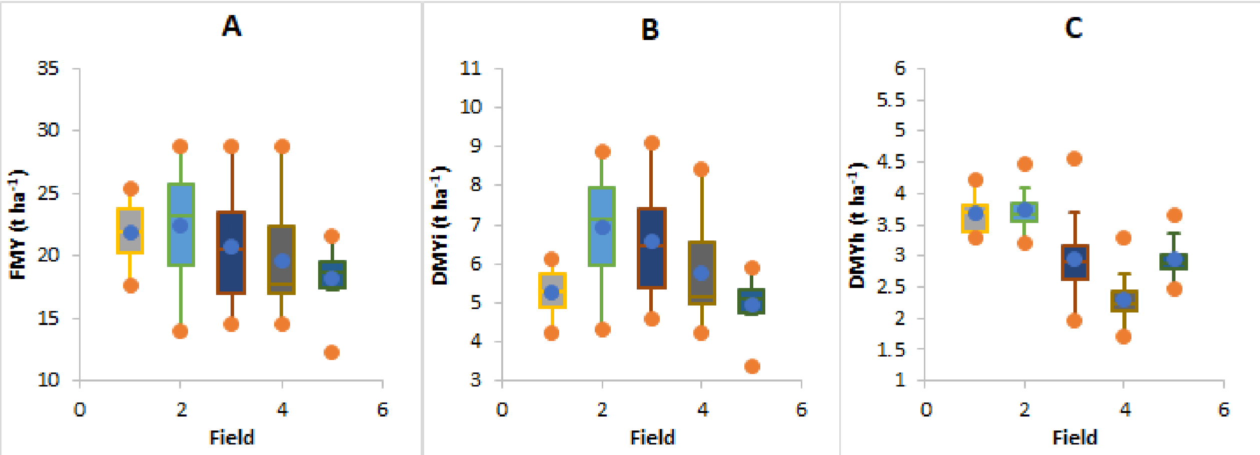

Figure 3. Distribution of fresh matter yield (A), initial dry matter yield (B), and harvested dry matter yield (C) of lucerne in the studied fields

Total Mechanical Losses of Dry Matter

Total Mechanical Losses (TML) ranged from 18.1% (Field 1) to 49.0% (Field 4), with an overall mean of 31.24% (Table 6). These results indicate that TML vary considerably according to climatic conditions during drying, particularly the occurrence of rainfall, and the efficiency of the harvest chain. Fields exposed to rainfall (Fields 1 to 3) generally exhibited higher losses, with the exception of Field 1, which was relatively spared. Older and less vigorous Fields (Fields 4 and 5) recorded higher mechanical losses even in the absence of rainfall.

Table 6. Total mechanical losses of initial DM and associated parameters for the studied fields

Field	Initial DM %	Oxidised DM %	Leached DM %	Harvested DM %	TML %
1	100	10.14	2	69.77	18.09
2	100	9.54	2	53.80	34.66
3	100	13.53	15	44.68	26.79
4	100	10.98	0	40.05	48.97
5	100	12.81	0	59.48	27.71

Homogeneity of Fresh Matter Yield

The absence of significant differences between fields for fresh matter yield ($p = 0.26$) contrasts sharply with the strong variability observed for harvested yield. This relative homogeneity suggests that local edaphoclimatic conditions exerted a predominant influence on primary production, partially masking the effects of cultural characteristics such as stand age, cultivar, and seeding rate. The arid climate of the Laghouat region, characterised by high temperatures, low rainfall, and intense solar radiation, imposes uniform water stress constraints on all fields, regardless of their management history. Under such conditions, irrigation management becomes the primary driver of primary productivity, rather than genetic or agronomic factors. These results are consistent with observations by several authors who emphasise the decisive role of environmental factors on initial lucerne productivity under water-limiting conditions (Geren et al., 2009; Alemayehu et al., 2020; Pourshirazi et al., 2022; Kim et al., 2023). The use of sprinkler irrigation systems, albeit with variable frequency and uniformity between fields, likely contributed to homogenising primary yields across sites.

Impact of Cultural Characteristics on Initial Dry Matter Yield

Despite the homogeneity observed for fresh matter yield, initial dry matter yield showed significant differences between fields ($p = 0.014$), particularly between Fields 2 and 5. This divergence reflects differences in dry matter content at cutting, which is strongly influenced by phenological stage and stand vigour. Field 2, harvested at early flowering with a two-year-old CUF 101 stand, benefited from an optimal balance between juvenile vigour and biomass accumulation, as reported by Martiniello et al. (1997), Stavarache et al. (2015), Karayilanli and Ayhan (2016).

In contrast, Field 5, although harvested at budding stage with a three-year-old stand, recorded the lowest DMYi despite its high leaf proportion (51.2% of DM). This apparent paradox can be explained by the earlier cutting stage, which corresponds to a lower level of carbohydrate accumulation in the plant. Harvesting at budding stage, whilst favourable for nutritional quality, systematically yields less dry matter per unit area compared with early flowering. The cutting stage thus represents a critical compromise between yield and quality that farmers in arid regions must manage carefully.

The morphological composition of the harvested material further illustrates this variability. The leaf-to-stem ratio ranged from 0.59 (Field 1) to 1.05 (Field 5), reflecting differences in phenological stage and stand structure. Leaves are the primary site of protein synthesis and photosynthetic activity, and their proportion in the harvested biomass is a reliable indicator of nutritional value. Fields with higher stem proportions, such as Field 1, produced more fibrous and energetically denser forage, whereas leaf-rich fields such as Field 5 offered higher crude protein content. This quantity-quality trade-off is well documented in the lucerne literature (Shinners et al., 2007; Milic et al., 2011) and carries significant practical implications for feed rationing in Algerian livestock systems.

Impact of Climatic Conditions on Post-Harvest Losses

Respiration Losses

Oxidation losses ranged from 9.54% (Field 2) to 13.53% (Field 3), values that are broadly comparable to those reported by Moser (1995) for field-dried legume hays (8-16%). Under the arid conditions of the Laghouat region, the high ambient temperatures during April (frequently exceeding 35°C during the day) accelerate forage respiration in the early hours following mowing, when the plant tissue is still hydrated and metabolically active. Respiration losses are particularly sensitive to temperature in the range of 25-40°C, where enzymatic activity remains elevated (Honig, 1980). Consequently, the combination of high temperatures and extended drying durations observed in this study creates conditions conducive to significant oxidative losses, even in the absence of rainfall.

The variability in respiration losses across fields is also attributable to differences in canopy density and initial moisture content. Denser, more mature stands retain moisture for longer within the windrow, prolonging the period of active respiration. This is consistent with the higher oxidation losses recorded for Field 3, which had the oldest stand (six years) and the longest drying duration. Optimising drying efficiency through appropriate windrow management - particularly by increasing windrow width to maximise solar exposure and air circulation - could substantially reduce these losses under arid conditions.

Leaching Losses

Leaching losses affected only Fields 1, 2, and 3, with the most severe impact on Field 3 (15%), which experienced four consecutive rainy days during the drying period. These values are consistent with those reported by Rotz and Muck (1994) and Rotz (2005), who documented leaching losses of 10-20% following sustained rainfall during field drying. Leaching acts primarily on soluble fractions of the forage, removing sugars, minerals, and water-soluble proteins, thereby degrading both the dry matter yield and nutritional quality of the recovered hay.

In arid regions, rainfall events during spring are characteristically unpredictable and of short duration but high intensity, as was the case during the April 2025 drying period in the Laghouat region. Such sporadic precipitation poses a particular challenge for harvest scheduling, as conventional meteorological forecasting is often unreliable at the local scale. The use of MERRA-2 satellite climate data, corrected according to the formulae developed by Khoudiri et al. (2025), represents a methodologically innovative and practically relevant approach for estimating climatic variables in the absence of local weather stations - a situation common to many arid agricultural regions of Algeria and North Africa more broadly. This approach could be integrated into decision-support tools for harvest scheduling, enabling farmers to time baling operations so as to minimise the probability of rain exposure.

Mechanical Losses and Harvest Chain Efficiency

The total mechanical losses observed in this study (18.1-49.0%) are of considerable magnitude and warrant careful contextualisation against reference thresholds established in the international literature. Excluding losses attributable to cutting height and tedding, acceptable losses for individual operations in the harvest chain are estimated at 2-4% for mowing, 3-6% for raking, and 3-11% for baling (Honig, 1980; Koegel et al., 1985; Rotz and Abrams, 1988; Rotz and Muck, 1994). This places the acceptable range for total mechanical losses between 8% and 21%.

Only Field 1 (18.1%) fell within this acceptable range, suggesting relatively efficient harvest management under the prevailing conditions. Fields 2, 3, and 5 (34.7%, 26.8%, and 27.7%, respectively) significantly exceeded these thresholds, whilst Field 4 (49.0%) recorded losses more than double the upper acceptable limit. These results indicate systemic inefficiencies in the harvest chain that cannot be attributed solely to climatic factors.

The elevated losses in Field 4 can be attributed to a convergence of unfavourable factors: an older stand (four years) characterised by reduced canopy vigour and increased stem fragility, an exceptionally high weed proportion (16.19%), and a lower seeding rate (40 $kg \cdot ha^{-1}$). Weed infestation has a dual adverse effect: it reduces the effective proportion of lucerne in the harvested material and alters the structural properties of the windrow, making mechanical recovery of stems more difficult during raking and baling. The presence of weeds of varying morphology and density modifies the flow of material through the baler, increasing leaf shatter and fragmentation losses.

More broadly, the high mechanical losses recorded across all fields reflect the limitations of the current harvest technology deployed in the region. The use of simple single-rotor rakes and small rectangular balers, whilst widely adopted due to their low cost and ease of maintenance, is associated with inherently higher leaf shatter losses compared with more advanced equipment such as belt rakes or large round balers. Raking operations, in particular, are a major source of mechanical leaf loss when carried out under adverse conditions - namely, when the forage is either too dry or too moist. In the context of the Laghouat region, where afternoon temperatures regularly exceed 38°C, raking performed during the hottest part of the day leads to excessive desiccation of the leaf lamina, greatly increasing fragmentation at contact points. Shifting raking operations to early morning, when relative humidity is higher and leaf moisture content slightly elevated, could substantially reduce these losses, as demonstrated by Rotz and Abrams (1988) and Shinners et al. (2007).

Limitations of the Study

Several limitations of this study should be acknowledged. First, the experiment was conducted on only five fields within a single municipality, which restricts the spatial representativeness of the results and limits the statistical power of between-field comparisons. Second, data were collected during a single cutting cycle in spring 2025; multi-year and multi-cut studies would be necessary to assess the temporal stability of the observed trends. Third, respiration and leaching losses were estimated using empirical models developed under temperate conditions (Honig, 1980; Rotz and Muck, 1994; Rotz, 2005), which may not be fully applicable to the specific climatic context of Algerian arid zones. The use of MERRA-2 satellite-derived climate data, whilst methodologically justified, introduces additional uncertainty into loss estimates. Fourth, total mechanical losses were assessed as a global balance without partitioning between individual harvest operations, preventing precise identification of the most critical loss points in the chain. Finally, a comprehensive economic valuation of dry matter and nutritional losses was beyond the scope of this study, but would be a valuable avenue for future research.

CONCLUSIONS

This study provides a quantitative assessment of mechanical dry matter losses during lucerne hay harvesting under the arid conditions of the Laghouat region, Algeria. Total mechanical losses ranged from 18.1% to 49.0% of initial dry matter yield, with an overall mean of 31.24%, substantially exceeding the acceptable thresholds established in the international literature (8-21%). These results highlight the limited efficiency of harvest chains currently practised in this region.

Climatic conditions during the drying period proved to be critical determinants of post-harvest losses, with leaching losses reaching 15% in the most severely affected field and respiration losses ranging from 9.54% to 13.53%. Weed infestation, reaching up to 16.19% in certain fields, represented an additional source of economic loss. The use of MERRA-2 satellite-derived climate data, corrected for local conditions, demonstrated its practical value as a substitute for ground-based meteorological measurements in data-scarce arid environments.

These findings underscore the need for targeted improvements in harvest chain management, including optimisation of raking timing, improved weed control, and the adoption of more efficient harvesting equipment adapted to local conditions. Future research should extend this approach across multiple cutting cycles and a wider geographical area whilst integrating an economic valuation of both dry matter and nutritional losses at the farm level.

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