

## Effect of management practices on yield and seed loss in durum wheat under arid conditions

Efecto de las prácticas de manejo en el rendimiento y la pérdida de semillas en trigo duro bajo condiciones áridas

Efeito das práticas de manejo no rendimento e na perda de sementes em trigo duro sob condições áridas

Mourad Hattab<sup>1\*</sup>    
Abderrahmane Kessaissia<sup>2</sup>  

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### Crop production

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University of Zulia, Faculty of Agronomy  
Bolivarian Republic of Venezuela

<sup>1</sup>Department of Agronomic Sciences. Faculty of Sciences. Laboratory of Biological and Agronomic Sciences (LSBA), Amar Telidji University, Laghouat, Algeria.

<sup>2</sup>National Institute for Forestry Research (NIFR). Experimental Station for the Protection of Watersheds, Ténès. Chlef, Algeria.

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### Abstract

Despite irrigation expansion, durum wheat yields in Algeria remain substantially below genetic potential. This study quantified emergence, natural, and mechanical losses under irrigated arid conditions in Laghouat Province, Algeria, during 2024-2025. Five experimental fields (Vitron variety) were monitored, measuring emergence densities, potential yield components, pre-harvest yield, and harvested yield. Emergence losses (24-43 %) were compensated through tillering ( $r = -0.996$ ,  $p \leq 0.001$ ), though excessive densities ( $> 600$  seeds.m<sup>2</sup>) increased losses without yield benefit. Potential yield ranged from 9.3 to 13.7 t.ha<sup>-1</sup>, with grain number per spike as primary determinant ( $r = 0.994$ ,  $p \leq 0.001$ ). Natural losses (12-38 %) were amplified by extreme weather (hail, 36 mm.h<sup>-1</sup> rainfall, May 14, 2025). Mechanical losses (31-47 %) exceeded international standards (3-7 %). Cumulative losses reached 54-60 % of potential, valorizing between 40 and 46 %. Optimization must prioritize mechanical loss reduction, legume rotations, and row seeding at moderate density.

## Resumen

A pesar de la expansión del riego, los rendimientos de trigo duro en Argelia permanecen sustancialmente por debajo del potencial genético. Este estudio cuantificó las pérdidas en emergencia, naturales y mecánicas bajo condiciones áridas irrigadas en la provincia de Laghouat, Argelia durante 2024-2025. Cinco campos experimentales (variedad Vitron) fueron monitoreados, midiendo densidades de emergencia, componentes del rendimiento potencial, rendimiento pre-cosecha y rendimiento cosechado. Las pérdidas en emergencia (24-43 %) fueron compensadas mediante ahijamiento ( $r = -0,996$ ;  $p \leq 0,001$ ), aunque densidades excesivas ( $> 600$  semillas.m<sup>-2</sup>) incrementaron las pérdidas sin beneficio en rendimiento. El rendimiento potencial varió entre 9,3 y 13,7 t.ha<sup>-1</sup>, siendo el número de granos por espiga el determinante principal ( $r = 0,994$ ;  $p \leq 0,001$ ). Las pérdidas naturales (12-38 %) fueron amplificadas por condiciones meteorológicas extremas (granizo, lluvia de 36 mm.h<sup>-1</sup>, 14 de mayo de 2025). Las pérdidas mecánicas (31-47 %) excedieron los estándares internacionales (3-7 %). Las pérdidas acumuladas alcanzaron 54-60 % del potencial, valorizando entre 40 y 46 %. La optimización debe priorizar la reducción por pérdidas mecánicas, rotaciones con leguminosas y siembra en línea con densidad moderada.

**Palabras clave:** trigo duro, pérdidas de rendimiento, emergencia, cosecha mecánica.

## Resumo

Apesar da expansão da irrigação, os rendimentos de trigo duro na Argélia permanecem substancialmente abaixo do potencial genético. Este estudo quantificou as perdas na emergência, naturais e mecânicas sob condições áridas irrigadas na província de Laghouat, Argélia durante 2024-2025. Cinco campos experimentais (variedade Vitron) foram monitorados, medindo densidades de emergência, componentes do rendimento potencial, rendimento pré-colheita e rendimento colhido. As perdas na emergência (24-43 %) foram compensadas através do ahijamento ( $r = -0,996$ ;  $p \leq 0,001$ ), embora densidades excessivas ( $> 600$  sementes.m<sup>-2</sup>) aumentassem as perdas sem benefício no rendimento. O rendimento potencial variou entre 9,3 e 13,7 t.ha<sup>-1</sup>, sendo o número de grãos por espiga o determinante principal ( $r = 0,994$ ;  $p \leq 0,001$ ). As perdas naturais (12-38 %) foram amplificadas por condições meteorológicas extremas (granizo, chuva de 36 mm.h<sup>-1</sup>, 14 de maio de 2025). As perdas mecânicas (31-47 %) excederam os padrões internacionais (3-7 %). As perdas acumuladas atingiram 54-60 % do potencial, valorizando entre 40 e 46 %. A otimização deve priorizar a redução de perdas mecânicas, rotações com leguminosas e semeadura em linha com densidade moderada.

**Palavras-chave:** trigo duro, perdas de rendimento, emergência, colheita mecânica.

## Introduction

Durum wheat (*Triticum durum* Desf.) is strategic for food security in Algeria. Despite considerable investments in irrigated area extension and cultivation modernization, average national yields remain low (1.6-4.2 t.ha<sup>-1</sup> in arid regions), well below genetic potential of improved varieties (6.0-8.0 t.ha<sup>-1</sup>) (Merouche *et al.*, 2014; MADR, 2021). This gap raises questions about loss magnitude throughout the crop cycle. Agronomic literature identifies three

critical loss phases: emergence losses from poor soil-seed contact, inadequate sowing depth, or early water stress (Zhai *et al.*, 2018); natural losses during maturation from biotic and abiotic factors (Grosse-Heilmann *et al.*, 2024); and mechanical harvest losses linked to improper combine settings (Kutzbach, 2000). However, integrated quantification under irrigated Saharan conditions remains largely lacking. Arid region durum wheat systems present marked specificities: systematic sprinkler irrigation, sandy-loam soils with low organic matter, extreme temperatures, and empirical practices. Field observations report considerable mechanical harvesting losses from operator training lack, machine obsolescence, and inadequate settings, but no precise quantitative data exists. This study quantifies durum wheat yield losses at three key stages—emergence, maturation, and mechanical harvest—under real irrigated Saharan conditions. Specific objectives are: (1) quantify emergence loss rates and analyze relationships with sowing practices; (2) estimate potential yield and identify major productivity determinants; (3) quantify natural losses and identify vulnerability factors; (4) quantify mechanical harvest losses; (5) establish integrated loss balance and prioritize improvement levers.

## Materials and methods

### Study location

Experimentation was conducted during the 2024-2025 season in Ben Nacer Benchohra municipality, Laghouat province, southern Algeria. This arid region presents annual precipitation below 200 mm, summer temperatures exceeding 40 °C, high evapotranspiration, and predominantly sandy-loam soils with low organic matter content (Hattab *et al.*, 2025).

### Plant material

The study focused on durum wheat (*Triticum durum* Desf.) variety Vitron, widely adopted by farmers in the region. This Spanish-origin variety presents medium to high straw height, a semi-early cycle, and good adaptation to arid and semi-arid conditions (Ladjal and Azouzi, 2014). Certified seeds, provided by the Algerian Interprofessional Cereals Office (OAIC), were treated with fungicide coating. Thousand-grain weight (TGW) and germination capacity (GC) presented some variability depending on the batches distributed to farmers.

### Characteristics of the experimental fields

Five durum wheat fields were randomly selected in the municipality of Ben Nacer Benchohra. This multi-site approach allows evaluating the impact of cultural practices under real production conditions. For each field, agronomic and cultural characteristics were comprehensively recorded to correlate them with the results obtained in the evaluated variables. Weather conditions being comparable between sites, observed variations are mainly attributable to cultural practices.

### Emergence loss estimation

Emergence loss assessment was performed at the 3-leaf stage (3 to 4 weeks after sowing, BBCH 13 according to Hack *et al.* (1992), the stage at which emergence is complete and stabilized. In each field, 10 quadrats of 1 m<sup>2</sup> were placed randomly avoiding edges ( $> 5$  m). Seedling counting was performed by successive 20 cm sections using two parallel guide sticks. Emergence density (ED, seedlings.m<sup>-2</sup>) was calculated as the average of the 10 quadrats. Viable seed sowing density (VSSD, seeds.m<sup>-2</sup>) was determined from the sowing rate, corrected by the TGW and GC of the batch used:

VSSD= [Sowing rate (g) × GC (relative frequency)]/[10 × TGW (g)]

The emergence loss rate (ELR, %) was calculated according to:

$$ELR = (VSSD - ED)/VSSD \times 100$$

### Potential yield estimation

Potential yield was estimated at the dough stage (BBCH 85 according to Hack *et al.* (1992), corresponding to physiological maturity where the grain has reached its maximum dry matter weight but still retains some moisture. In each field, 10 quadrats of 1 m<sup>2</sup> were randomly placed avoiding edges and atypical zones (machinery tracks, lodging areas, etc.). Measurement protocol: (1) Comprehensive counting of fertile spikes.m<sup>-2</sup> (SN); (2) Random sampling of 10 spikes.quadrat.m<sup>-2</sup>; (3) Manual threshing and counting of grains from each spike; (4) Calculation of average grain number.spike.m<sup>-2</sup> (GNS); (5) Calculation of grain number.m<sup>-2</sup> (GN.m<sup>-2</sup> = SN × GNS); (6) Determination of grain weight.m<sup>-2</sup> from actual TGW measured on samples before harvest: GW.m<sup>-2</sup> = (GN.m<sup>-2</sup> × TGW<sub>A</sub>)/1000; (7) Extrapolation of potential yield (PY) per hectare:

$$PY (q.ha^{-1}) = \text{Average GW.m}^{-2} (g) \times 10^{-1}$$

### Natural loss estimation

Natural losses, occurring between the dough stage and the day before harvest, result from biotic factors (diseases, pests) and abiotic factors (violent winds, excessive desiccation, precipitation). They were quantified by the difference between potential yield and pre-harvest yield. One day before scheduled harvest (BBCH 92 stage according to Hack *et al.*, 1992), 200 spikes were randomly collected at 10 locations per field (20 spikes.location<sup>-1</sup>). Only spikes still carried by plants were sampled. All grains were counted to calculate the average grain number.spike.m<sup>-1</sup> before harvest (GNS<sub>BH</sub>). The actual TGW (TGW<sub>A</sub>) was determined on three samples of 1000 grains. Pre-harvest yield (PHY) was calculated according to this equation:

$$GN.m^{-2}_{BH} = GNS_{BH} \times SN$$

$$GW.m^{-2}_{BH} = (GN.m^{-2}_{BH} \times TGW_A)/1000$$

$$PHY (q.ha^{-1}) = GW.m^{-2}_{BH} \times 10^{-1}$$

Natural losses (NL) and their rate (NLR) were calculated:

$$NL (q.ha^{-1}) = PY - PHY$$

$$NLR (\%) = (PY - PHY)/PY \times 100$$

### Mechanical harvest loss estimation

Mechanical harvest losses, mainly due to improper combine harvester settings, were quantified by the difference between pre-harvest yield and actual harvested yield. Harvested yield (HY) was obtained by farmer declaration at the end of harvest. Farmers of the five studied fields having delivered their harvest to the Algerian Interprofessional Cereals Office (OAIC) benefited from certified scale weighing, guaranteeing good reliability and traceability of actual harvested yield. This method reflects actually valorized yield and local yield measurement practices.

Mechanical harvest losses (ML) and their rate (MLR) were calculated:

$$ML (q.ha^{-1}) = PHY - HY$$

$$MLR (\%) = (PHY - HY)/PHY \times 100$$

### Total loss balance

Total losses (TL) from physiological maturity to the end of harvest were calculated as the sum of natural losses and mechanical losses:

$$TL (q.ha^{-1}) = NL + ML = PY - HY$$

The total loss rate (TLR) relative to potential yield was expressed:

$$TLR (\%) = (PY - HY)/PY \times 100$$

This balance allows quantifying the gap between productive potential and valorized yield, and determining the relative contribution of each loss type.

### Statistical analyses

For each variable, means, standard deviations, and coefficients of variation were calculated. One-way ANOVA tested significant differences between fields, with Tukey's HSD test ( $p \leq 0.05$ ) identifying homogeneous groups. Pearson correlation matrix was established between 13 variables to identify significant relationships and prioritize yield determinants. Analyses were performed with XLSTAT version 2025.1 ( $\alpha = 0.05$ ).

## Results and discussion

### Characteristics of the five experimental durum wheat fields

The five selected fields present commonalities guaranteeing comparability and differences allowing analysis of practice impacts (Table 1). Areas vary from 2 to 4.5 ha (average 3.06 ha) with flat topography, eliminating slope effects. The Vitron variety was cultivated in all fields, with homogeneous seed quality (TGW 50.8 ± 0.84 g, GC 94.8 ± 0.84 %). Sowing dates were grouped (November 15-20, 2024) except Field 4 (December 4). Harvest dates ranged from June 25 to July 15, 2025.

Uniform practices included standardized soil tillage (plowing + disc harrowing without finishing), organic manure application, basal mineral fertilization, mobile sprinkler irrigation, no plant protection, and mechanical harvest. Sowing rates varied considerably (2.22-4 q.ha<sup>-1</sup>), translating into densities of 435-800 seeds.m<sup>-2</sup>. Previous crops showed diversity: durum wheat (Fields 1, 2, 4), alfalfa (Field 3), and fallow (Field 5). Sowing methods differed: broadcast (Fields 1, 2, 3) versus row seeder (Fields 4, 5). Top-dressing nitrogen was applied in four fields (1, 2, 4, 5), but not Field 3. Chemical weeding occurred in three fields (1, 2, 5).

### Durum wheat emergence losses

As shown in Table 2, emergence assessment at the 3-leaf stage revealed average densities ranging from 310.9 (Field 5) to 430.0 seedlings.m<sup>-2</sup> (Fields 3, 4), though variance analysis showed no significant differences ( $p = 0.191$ ) due to high intra-plot variability. Field 4 (row seeded, moderate density) displayed the most regular emergence, while Field 1 (broadcast, high density) showed highest variability. The apparent homogeneity despite contrasting practices is explained by irrigation compensating for unfavorable factors. Under irrigated conditions, constant water availability attenuates the impact of unfavorable factors such as poor soil-seed contact or inadequate sowing depth (Zahiry and Hamayoun, 2020).

Absolute losses showed highly significant differences ( $p \leq 0.001$ ), varying from 98.1 (Field 5) to 330.0 seeds.m<sup>-2</sup> (Field 3), revealing a density-dependent relationship: excessive density generates increased losses without proportional benefit (Mahdi *et al.*, 1998). Field 3 (800 seeds.m<sup>-2</sup>) required 1.77 seeds per emerged seedling versus 1.32 for Field 5 (435 seeds.m<sup>-2</sup>), representing ~92 kg.ha<sup>-1</sup> additional cost. Relative loss rates varied from 24.0 % to 43.4 %, remaining high compared to agronomic standards (10-20 % under optimal conditions, Singh *et al.*, 2025), explained by the absence of soil finishing operations. The combination row seeding + moderate density (Field 4: 600 seeds.m<sup>-2</sup>) appears optimal.

### Potential yield and its components

Potential yield at dough stage (BBCH 85) represents maximum theoretical yield absent losses between maturity and harvest (Table

**Table 1. Agronomic characteristics and cultural practices of the experimental fields with durum wheat**

| Parameter                               | Field 1     | Field 2     | Field 3    | Field 4     | Field 5    | Mean ± SD   |
|---|-------------|-------------|------------|-------------|------------|-------------|
| Area (ha)                               | 3.3         | 2.5         | 3.0        | 2.0         | 4.5        | 3.06 ± 0.96 |
| Topography                              | Flat        | Flat        | Flat       | Flat        | Flat       | -           |
| Previous crop                           | Durum wheat | Durum wheat | Alfalfa    | Durum wheat | Fallow     | -           |
| Variety                                 | Vitron      | Vitron      | Vitron     | Vitron      | Vitron     | -           |
| TGW (g)                                 | 52          | 51          | 50         | 50          | 51         | 50.8 ± 0.84 |
| GC (%)                                  | 95          | 94          | 95         | 96          | 94         | 94.8 ± 0.84 |
| Sowing date                             | 20/11/2024  | 15/11/2024  | 20/11/2024 | 04/12/2024  | 20/11/2024 | -           |
| Sowing rate (q.ha <sup>-1</sup> )       | 3.64        | 3.00        | 4.00       | 3.00        | 2.22       | 3.17 ± 0.64 |
| Sowing density (seeds.m <sup>-2</sup> ) | 700         | 588         | 800        | 600         | 435        | 625 ± 137   |
| Soil tillage                            | P+DH        | P+DH        | P+DH       | P+DH        | P+DH       | -           |
| Sowing method                           | Broadcast   | Broadcast   | Broadcast  | Row seeder  | Row seeder | -           |
| Organic manure                          | Yes         | Yes         | Yes        | Yes         | Yes        | -           |
| Basal fertilizer                        | Yes         | Yes         | Yes        | Yes         | Yes        | -           |
| Top-dressing N                          | Yes         | Yes         | No         | Yes         | Yes        | -           |
| Chemical weeding                        | Yes         | Yes         | No         | No          | Yes        | -           |
| Plant protection                        | No          | No          | No         | No          | No         | -           |
| Irrigation                              | MSS         | MSS         | MSS        | MSS         | MSS        | -           |
| Harvest                                 | CH          | CH          | CH         | CH          | CH         | -           |
| Harvest date                            | 05/07/2025  | 25/06/2025  | 15/07/2025 | 13/07/2025  | 11/07/2025 | -           |

TGW: Thousand-Grain Weight; GC: Germination Capacity; P+H: Plowing + Disc Harrowing; MSS: Mobile Sprinkler System; CH: Combine Harvester; SD: Standard Deviation.

**Table 2. Emergence densities and loss rates in the five studied fields.**

| Field     | SD (seeds.m <sup>-2</sup> ) | VSSD (seeds.m <sup>-2</sup> ) | ED (seedlings.m <sup>-2</sup> ) | CV (%) | NEVSSD (seeds.m <sup>-2</sup> ) | CV (%) | ELR (%)                    | CV (%) |
|-----------|-----------------------------|-------------------------------|---------------------------------|--------|---------------------------------|--------|----------------------------|--------|
| 1         | 700                         | 665                           | 383.56 ± 166.02 <sup>a</sup>    | 43.28  | 281.44 ± 166.02 <sup>ab</sup>   | 59     | 42.32 ± 24.97 <sup>a</sup> | 59     |
| 2         | 588                         | 553                           | 383.33 ± 083.14 <sup>a</sup>    | 21.69  | 169.67 ± 083.14 <sup>bc</sup>   | 49     | 30.68 ± 15.03 <sup>a</sup> | 49     |
| 3         | 800                         | 760                           | 430.00 ± 141.93 <sup>a</sup>    | 33.00  | 330.00 ± 141.93 <sup>a</sup>    | 43     | 43.42 ± 18.67 <sup>a</sup> | 43     |
| 4         | 600                         | 576                           | 430.00 ± 072.33 <sup>a</sup>    | 16.82  | 146.00 ± 072.33 <sup>bc</sup>   | 49.54  | 25.35 ± 12.56 <sup>a</sup> | 49.54  |
| 5         | 435                         | 409                           | 310.89 ± 082.32 <sup>a</sup>    | 26.48  | 098.11 ± 082.32 <sup>c</sup>    | 83.9   | 23.99 ± 20.13 <sup>a</sup> | 83.9   |
| ANOVA (p) | -                           | -                             | 0.191 <sup>NS</sup>             | -      | ≤ 0.001 <sup>***</sup>          | -      | 0.089 <sup>NS</sup>        | -      |

SD: Sowing Density; VSSD: Viable Seed Sowing Density; ED: Emergence Density; NEVSSD: Non-emerged Viable Seed Sowing Density; ELR: Emergence Loss Rate; CV: Coefficient of Variation; NS: Not Significant (p > 0.05); \*\*\*: Highly Significant (p ≤ 0.001). Superscript letters indicate homogeneous groups according to Tukey's test (HSD) at 5 % threshold.

3). Fertile spike densities varied minimally (438-473 spikes.m<sup>-2</sup>) with no significant differences (p = 0.954), contrasting sharply with emergence density heterogeneity. This results from tillering compensation (indices 1.08-1.41). Field 5, with lowest emergence (311 seedlings.m<sup>-2</sup>), compensated through intense tillering (1.41) to reach 438 spikes.m<sup>-2</sup>, while Fields 3-4 limited tillering (1.10, 1.08). This phenotypic plasticity is well documented: low-density stands favor secondary tiller emission thanks to lower competition for space, light, and resources (Kondic *et al.*, 2017; Liu *et al.*, 2023).

Grain number.spike<sup>-1</sup> showed highly significant differences (p ≤ 0.001), varying from 38 (Field 2) to 53 grains.spike<sup>-1</sup> (Field 5). Field 3 (alfalfa previous crop) displayed excellent spike fertility (52), suggesting favorable nitrogen nutrition effects (Peoples *et al.*, 2009; Ni *et al.*, 2026). Field 5 presented highest grain number.spike<sup>-1</sup> (53), illustrating classic compensation (Slafer *et al.*, 2014). Grain number.m<sup>-2</sup> showed significant differences (p = 0.026), with

Field 3 clearly standing out (24264 grains.m<sup>-2</sup>), combining high spike density and maximum grain number.spike<sup>-1</sup>. Potential yield showed very significant differences (p = 0.006), varying from 9.29 (Field 2) to 13.65 t.ha<sup>-1</sup> (Field 3). Field 3 validated the favorable alfalfa previous crop effect, reaching 13.65 t.ha<sup>-1</sup> without top-dressing nitrogen. Field 5 achieved comparable yield (13.40 t.ha<sup>-1</sup>) through different strategy: low emergence → intense tillering → high spike fertility → maximum TGW (57.97 g). Grain number.spike<sup>-1</sup> emerged as the major potential yield determinant under these conditions.

#### Natural losses

Natural losses occur between dough stage and pre-harvest, from biotic and abiotic factors. On May 14, 2025, exceptional weather occurred: heavy hail and 36 mm.h<sup>-1</sup> intense rain, extreme for a region averaging < 200 mm annually. This violent episode during critical maturation caused mechanical shattering, lodging, and potential sprouting (Bucheli *et al.*, 2024). Spatial hailstorm heterogeneity

**Table 3. Potential yield components of the five studied fields.**

| Field     | SN.m <sup>-2</sup>     | CV (%) | TI   | GNS                      | CV (%) | GN.m <sup>-2</sup>         | CV (%) | TGW <sub>A</sub> (g)      | CV (%) | PY (t.ha <sup>-1</sup> )   | CV (%) |
|-----------|------------------------|--------|------|--------------------------|--------|----------------------------|--------|---------------------------|--------|----------------------------|--------|
| 1         | 468 ± 114 <sup>a</sup> | 24.36  | 1.22 | 41 ± 11.00 <sup>b</sup>  | 26.83  | 18935 ± 6137 <sup>ab</sup> | 32.41  | 54.21 ± 0.77 <sup>c</sup> | 1.42   | 10.26 ± 3.32 <sup>ab</sup> | 32.41  |
| 2         | 462 ± 127 <sup>a</sup> | 27.49  | 1.20 | 38 ± 04.00 <sup>b</sup>  | 10.53  | 17117 ± 4183 <sup>b</sup>  | 24.44  | 54.28 ± 0.43 <sup>c</sup> | 0.79   | 09.29 ± 2.27 <sup>b</sup>  | 24.44  |
| 3         | 473 ± 117 <sup>a</sup> | 24.74  | 1.10 | 52 ± 07.00 <sup>a</sup>  | 13.46  | 24264 ± 6292 <sup>a</sup>  | 25.93  | 56.29 ± 0.13 <sup>b</sup> | 0.23   | 13.65 ± 3.54 <sup>a</sup>  | 25.93  |
| 4         | 464 ± 300 <sup>a</sup> | 64.66  | 1.08 | 46 ± 05.00 <sup>ab</sup> | 10.87  | 21057 ± 2357 <sup>ab</sup> | 11.19  | 55.85 ± 0.21 <sup>b</sup> | 0.38   | 11.76 ± 1.31 <sup>ab</sup> | 11.20  |
| 5         | 438 ± 109 <sup>a</sup> | 24.89  | 1.41 | 53 ± 04.00 <sup>a</sup>  | 07.55  | 23126 ± 6328 <sup>ab</sup> | 27.36  | 57.97 ± 0.65 <sup>a</sup> | 1.21   | 13.40 ± 3.66 <sup>a</sup>  | 27.36  |
| ANOVA (p) | 0.954 <sup>NS</sup>    | -      | -    | ≤ 0.001 <sup>***</sup>   | -      | 0.026 <sup>*</sup>         | -      | ≤ 0.001 <sup>***</sup>    | -      | 0.006 <sup>**</sup>        | -      |

SN: Average Spike Number; TI: Tilling Index; GNS: Average Grain Number.spike<sup>-1</sup>; GN: Average Grain Number; CV: Coefficient of Variation; PY: Potential Yield; TGW<sub>A</sub>: Actual Thousand-Grain Weight (1 day before harvest); NS: Not Significant (p > 0.05); \*: Significant (p ≤ 0.05); \*\*: Very Significant (p ≤ 0.01); \*\*\*: Highly Significant (p ≤ 0.001). Superscript letters indicate homogeneous groups according to Tukey's test (HSD) at 5 % threshold.

(Zhou and Vilar-Zanon, 2025) partly explains high loss variability. Comparative analysis revealed widespread grain number.spike<sup>-1</sup> decreases (Table 4), varying from 7 grains.spike<sup>-1</sup> (Field 3, 13.5 %) to 16 grains.spike<sup>-1</sup> (Field 1, 39 %). Field 1 recorded severe degradation (41 to 25 grains.spike<sup>-1</sup>), causing yield collapse to 6.33 t.ha<sup>-1</sup> versus 10.26 t.ha<sup>-1</sup> potential. Field 3, despite highest potential (13.65 t.ha<sup>-1</sup>), maintained 11.98 t.ha<sup>-1</sup> pre-harvest yield, suggesting better structural resistance from alfalfa previous crop (Peoples *et al.*, 2009).

Natural loss rates showed significant differences (p = 0.031), varying from 12.28 % (Field 3) to 38.27 % (Field 1). Field 3's remarkable resilience (12.28 %) is attributable to alfalfa protective effects (soil structure, root anchorage, lodging resistance). Field 1's extreme vulnerability (38.27 %) resulted from phenological heterogeneity (CV 43.3 % emergence), lodging sensitivity from broadcast high-density seeding (700 seeds.m<sup>-2</sup>), and possible maximum hail exposure. Observed rates (12-38 %) must be interpreted within the May 14 extreme event context and don't represent «normal» losses but illustrate vulnerability to extreme climatic hazards.

#### Mechanical harvest losses and valorized yield

Mechanical losses occur during combine harvesting. Actually harvested yield (HY), obtained via OAIC certified weighing, varied from 41 (Field 1) to 6.0 t.ha<sup>-1</sup> (Field 3) (Table 5). Field 3 maintained dominance with 6.0 t.ha<sup>-1</sup>, from exceptional potential (13.65 t.ha<sup>-1</sup>) and low natural loss rate (12.28 %). Fields 1-2 showed lowest yields (4.1, 4.3 t.ha<sup>-1</sup>) from cumulative moderate potential, high natural losses (38.27 %, 27.20 %), and significant mechanical losses (31.89 %, 31.38 %). Field 1 ultimately valorized only 40 % of initial potential.

Absolute mechanical losses showed highly significant differences (p ≤ 0.001), varying from 2.23 to 5.98 t.ha<sup>-1</sup>. Field 3 presents an apparent paradox: highest harvested yield yet most significant absolute losses (5.98 t.ha<sup>-1</sup>), explained by exceptionally high pre-harvest yield

(11.98 t.ha<sup>-1</sup>). This demonstrates absolute mechanical losses increase proportionally to available yield (Kutzbach, 2000). Mechanical loss rates varied from 31.38 % to 47.40 %, far exceeding agronomic standards (3 % Delchev and Trendafilov, 2013; 2.5 % Al-Sammarraie and Alhadithi, 2021; 6.83 %, Abdulla *et al.*, 2025). Field 3 presented highest mechanical rate (47.40 %), possibly from very high pre-harvest yield exceeding combine capacity, generating clogging losses (Kutzbach, 2000), or improper settings in dense productive stands. Although harvest occurred under dry conditions, the May 14 episode had lasting repercussions: partial lodging generating increased losses from cutting difficulty, cutter bar clogging, and ground grain losses (Dahiya *et al.*, 2018; Yadav *et al.*, 2024). High losses also result from improper combine settings, operator training lack, and machine obsolescence. Cumulative natural and mechanical losses lead to dramatic total loss rates of 54-60 %, valorizing only 40-46 % of potential. Priority improvements include: operator training programs on optimal combine settings; finely adapting machine parameters to field yield; renewing obsolete combines; adapting cutting height and speed in lodging cases; determining optimal harvest date balancing natural and mechanical loss reduction.

#### Correlations between studied variables

Correlation analysis between 13 variables reveals key relationships (Table 6). Sowing density correlated with spike number.m<sup>-2</sup> (r = 0.933, p ≤ 0.05) and emergence loss rate (r = 0.897, p ≤ 0.05), confirming excessive densities (> 600 seeds.m<sup>-2</sup>) generate increased losses without benefit. Tilling index and emergence density showed almost perfect negative correlation (r = -0.996, p ≤ 0.001), confirming phenotypic compensation explaining why fields reached similar spike densities (438-473 spikes.m<sup>-2</sup>) despite contrasting emergence (311-430 seedlings.m<sup>-2</sup>).

Grain number.spike<sup>-1</sup> emerged as major yield determinant (r = 0.994, p ≤ 0.001), with strong correlations to grain number.m<sup>-2</sup> (r =

**Table 4. Pre-harvest yield components and natural losses.**

| Field     | GNS <sub>BH</sub> | GN.m <sup>-2</sup> <sub>BH</sub> | CV (%) | TGW <sub>A</sub> (g)      | CV (%) | PHY (t.ha <sup>-1</sup> )  | CV (%) | NL (t.ha <sup>-1</sup> ) | CV (%) | NLR (%)                     | CV (%) |
|-----------|-------------------|----------------------------------|--------|---------------------------|--------|----------------------------|--------|--------------------------|--------|-----------------------------|--------|
| 1         | 25                | 11688 ± 2847 <sup>c</sup>        | 24.36  | 54.21 ± 0.77 <sup>c</sup> | 1.42   | 06.33 ± 1.54 <sup>c</sup>  | 24.35  | 3.92 ± 1.54 <sup>a</sup> | 39.28  | 38.27 ± 15.04 <sup>a</sup>  | 39.30  |
| 2         | 27                | 12461 ± 3421 <sup>c</sup>        | 27.45  | 54.28 ± 0.43 <sup>c</sup> | 0.79   | 06.76 ± 1.85 <sup>c</sup>  | 27.45  | 2.52 ± 1.85 <sup>a</sup> | 73.49  | 27.20 ± 19.98 <sup>ab</sup> | 73.46  |
| 3         | 45                | 21285 ± 5281 <sup>a</sup>        | 24.81  | 56.29 ± 0.13 <sup>b</sup> | 0.23   | 11.98 ± 2.97 <sup>a</sup>  | 24.81  | 1.67 ± 2.97 <sup>a</sup> | 177.28 | 12.28 ± 21.77 <sup>b</sup>  | 177.28 |
| 4         | 33                | 15296 ± 1002 <sup>bc</sup>       | 06.55  | 55.85 ± 0.21 <sup>b</sup> | 0.38   | 08.54 ± 0.56 <sup>bc</sup> | 06.55  | 3.21 ± 0.56 <sup>a</sup> | 17.41  | 27.36 ± 04.76 <sup>ab</sup> | 17.40  |
| 5         | 40                | 17500 ± 4365 <sup>ab</sup>       | 24.94  | 57.97 ± 0.65 <sup>a</sup> | 1.21   | 10.14 ± 2.53 <sup>ab</sup> | 24.94  | 3.26 ± 2.53 <sup>a</sup> | 77.58  | 24.33 ± 18.87 <sup>ab</sup> | 77.56  |
| ANOVA (p) | -                 | ≤ 0.001 <sup>***</sup>           | -      | ≤ 0.001 <sup>***</sup>    | -      | ≤ 0.001 <sup>***</sup>     | -      | 0.165 <sup>NS</sup>      | -      | 0.031 <sup>*</sup>          | -      |

GNS<sub>BH</sub>: Average Grain Number.spike<sup>-1</sup> Before Harvest; GN.m<sup>-2</sup><sub>BH</sub>: Average Grain Number.m<sup>-2</sup> Before Harvest; TGW<sub>A</sub>: Actual Thousand-Grain Weight; PHY: Pre-Harvest Yield; NL: Natural Losses; NLR: Natural Losses Rate; CV: Coefficient of Variation; NS: Not Significant (p > 0.05); \*: Significant (p ≤ 0.05); \*\*\*: Highly Significant (p ≤ 0.001). Superscript letters indicate homogeneous groups according to Tukey's test (HSD) at 5 % threshold.

**Table 5. Harvested yields and mechanical harvest losses.**

| Field     | PY (t.ha <sup>-1</sup> ) | PHY (t.ha <sup>-1</sup> ) | HY (t.ha <sup>-1</sup> ) | ML (t.ha <sup>-1</sup> )  | CV (%) | MLR (%)                    | CV (%) | TL (t.ha <sup>-1</sup> ) |
|-----------|--------------------------|---------------------------|--------------------------|---------------------------|--------|----------------------------|--------|--------------------------|
| 1         | 10.26                    | 06.33                     | 4.1                      | 2.23 ± 1.54 <sup>b</sup>  | 69.00  | 31.89 ± 15.70 <sup>a</sup> | 49.23  | 6.16                     |
| 2         | 09.29                    | 06.76                     | 4.3                      | 2.46 ± 1.85 <sup>b</sup>  | 75.37  | 31.38 ± 21.09 <sup>a</sup> | 67.21  | 4.99                     |
| 3         | 13.65                    | 11.98                     | 6.0                      | 5.98 ± 2.97 <sup>a</sup>  | 49.71  | 47.40 ± 11.52 <sup>a</sup> | 24.30  | 7.65                     |
| 4         | 11.76                    | 08.54                     | 5.0                      | 3.54 ± 0.56 <sup>ab</sup> | 15.81  | 41.25 ± 03.78 <sup>a</sup> | 09.16  | 6.76                     |
| 5         | 13.40                    | 10.14                     | 5.6                      | 4.54 ± 2.53 <sup>ab</sup> | 55.67  | 41.26 ± 16.27 <sup>a</sup> | 39.43  | 7.80                     |
| ANOVA (p) | 0.006**                  | ≤ 0.001***                | -                        | ≤ 0.001***                | -      | 0.092 <sup>NS</sup>        | -      | -                        |

PY: Potential Yield; PHY: Pre-Harvest Yield; HY: Harvested Yield; ML: Mechanical Losses; MLR: Mechanical Loss Rate; TL: Total Losses; CV: Coefficient of Variation; NS: Not Significant (p > 0.05); \*\*: Very Significant (p ≤ 0.01); \*\*\*: Highly Significant (p ≤ 0.001). Superscript letters indicate homogeneous groups according to Tukey's test (HSD) at 5 % threshold.

0.979, p ≤ 0.01), TGW<sub>A</sub> (r = 0.928, p ≤ 0.05), and pre-harvest yield (r = 0.919, p ≤ 0.05). Grain number.m<sup>-2</sup> correlated almost perfectly with potential yield (r = 0.995, p ≤ 0.001), mechanical losses (r = 0.948, p ≤ 0.05), and harvested yield (r = 0.952, p ≤ 0.05). This hierarchy (GNS > GN.m<sup>-2</sup> > TGW<sub>A</sub>) confirms grain number as the main lever. Potential yield correlated strongly with pre-harvest yield (r = 0.941, p ≤ 0.05) and absolute mechanical losses (r = 0.932, p ≤ 0.05), showing high-yield fields generate more losses due to large biomass exceeding combine capacity. Pre-harvest yield best predicts harvested yield (r = 0.993, p ≤ 0.001). Natural and mechanical loss rates weren't correlated (r = -0.833), indicating independent determinants. Emergence loss rate wasn't correlated with any yield variable, confirming tillering compensation neutralized its impact—emergence optimization targets economic efficiency rather than yield improvement.

## Conclusion

This study reveals catastrophic cumulative losses of 54-60 % of durum wheat potential yield in Laghouat Province (2024-2025). Emergence losses (24-43 %) are compensated by tillering, though excessive densities (> 600 seeds.m<sup>-2</sup>) waste seeds. Grain number.spike<sup>-1</sup> is the major determinant. Natural losses (12-38 %) were amplified by extreme weather, showing 38.27 % vulnerability in monoculture versus 12.28 % after alfalfa. Mechanical losses (31-47 %) exceed international standards (3-7 %) and constitute the major bottleneck. Optimization must prioritize legume rotations, row seeding at 500-600 seeds.m<sup>-2</sup>,

mechanical loss reduction through operator training, and climate adaptation strategies for Saharan cereal food security.

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**Table 6. Correlation between studied variables.**

| Variables        | SD       | ED       | ELR           | TI               | SN             | GNS      | GN             | TGW <sub>A</sub> | PY              | PHY           | NLR            | MLR            | HY              |
|------------------|----------|----------|---------------|------------------|----------------|----------|----------------|------------------|-----------------|---------------|----------------|----------------|-----------------|
| SD               | <b>1</b> | 0.783    | <b>0.897*</b> | -0.739           | <b>0.933*</b>  | -0.100   | 0.096          | -0.459           | -0.002          | 0.154         | -0.245         | 0.196          | 0.044           |
| ED               |          | <b>1</b> | 0.436         | <b>-0.996***</b> | <b>0.898*</b>  | -0.177   | 0.006          | -0.429           | -0.077          | 0.085         | -0.246         | 0.253          | 0.018           |
| ELR              |          |          | <b>1</b>      | -0.378           | 0.746          | -0.117   | 0.039          | -0.452           | -0.045          | 0.055         | -0.078         | 0.006          | -0.058          |
| TI               |          |          |               | <b>1</b>         | <b>-0.880*</b> | 0.222    | 0.047          | 0.451            | 0.126           | -0.043        | 0.227          | -0.215         | 0.019           |
| SN               |          |          |               |                  | <b>1</b>       | -0.370   | -0.176         | -0.669           | -0.271          | -0.101        | -0.070         | -0.005         | -0.199          |
| GNS              |          |          |               |                  |                | <b>1</b> | <b>0.979**</b> | <b>0.928*</b>    | <b>0.994***</b> | <b>0.919*</b> | -0.673         | <b>0.898*</b>  | <b>0.944*</b>   |
| GN               |          |          |               |                  |                |          | <b>1</b>       | 0.838            | <b>0.995***</b> | <b>0.947*</b> | -0.718         | <b>0.948*</b>  | <b>0.952*</b>   |
| TGW <sub>A</sub> |          |          |               |                  |                |          |                | <b>1</b>         | <b>0.888*</b>   | 0.779         | -0.546         | 0.743          | 0.841           |
| PY               |          |          |               |                  |                |          |                |                  | <b>1</b>        | <b>0.941*</b> | -0.707         | <b>0.932*</b>  | <b>0.956*</b>   |
| PHY              |          |          |               |                  |                |          |                |                  |                 | <b>1</b>      | <b>-0.902*</b> | <b>0.960**</b> | <b>0.993***</b> |
| NLR              |          |          |               |                  |                |          |                |                  |                 |               | <b>1</b>       | -0.833         | <b>-0.878*</b>  |
| MLR              |          |          |               |                  |                |          |                |                  |                 |               |                | <b>1</b>       | <b>0.959**</b>  |
| HY               |          |          |               |                  |                |          |                |                  |                 |               |                |                | <b>1</b>        |

\* p ≤ 0.05; \*\* p ≤ 0.01; \*\*\* p ≤ 0.001. SD: Sowing Density; ED: Emergence Density; ELR: Emergence Loss Rate; TI: Tillering Index; SN: Spike Number.m<sup>-2</sup>; GNS: Grain Number/Spike; GN: Grain Number.m<sup>-2</sup>; TGW<sub>A</sub>: Actual Thousand-Grain Weight; PY: Potential Yield; PHY: Pre-Harvest Yield; NLR: Natural Loss Rate; MLR: Mechanical Loss Rate; HY: Harvested Yield.

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