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Full length article

Optimised nitrogen fertilisation strategies improve productivity and the environmental impact of durum wheat cultivation under Mediterranean drought conditions

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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

The study compared the response of one landrace (*Russello Priziusa*), one ancient variety (*Senatore Cappelli*), and two modern genotypes under conventional management, slow-release nitrogen fertilisation, and organic management in a semi-arid Mediterranean environment characterised by Xerofluvent soil. Agronomic traits, including grain yield, protein content, grain quality (white starchy kernels, WS; shrunken kernels, SK), and nitrogen apparent recovery efficiency (NARE), were evaluated. The wheat landrace and the ancient variety were suited to multiple management strategies, particularly organic and slow-release fertilisation. These genotypes exhibited significantly lower SK values than the modern varieties, while maintaining comparable NARE, despite their lower yield under conventional management. Overall, the results highlight the importance of optimising management practices for both modern and traditional wheat systems to enhance food security and promote sustainable production in the Mediterranean region.

1. Introduction

Optimal nitrogen fertilisation of durum wheat (*Triticum turgidum* subsp. durum (Desf.)) plays a crucial role in increasing yield, improving nutrient use efficiency, reducing nitrogen pollution, and thereby ensuring sustainable agricultural practices (Yao et al., 2015). Optimal nitrogen management must account for the interaction between soil nitrogen availability and crop demand, which varies across phenological stages (Ashraf and Farooq-E-Azam., 1998; Campbell et al., 1993; Cui et al., 2010). However, this synchronisation is increasingly disrupted under Mediterranean drought conditions, where rising temperatures and water scarcity alter crop development and shorten the window for nitrogen uptake (Ding et al., 2018; Fatima et al., 2020; Skendžić et al., 2023; Zhao et al., 2024; Acevedo et al., 2002; Tarín-Carrasco et al., 2024).

In this context, fertilisation strategies that maintain a prolonged and steady nitrogen supply are essential. Slow-release (SRF) and controlled-release (CRF) nitrogen fertilisers enhance synchronisation between nitrogen availability and crop nitrogen demand (De Oliveira et al., 2018), improving productivity while reducing environmental losses (Cheng et al., 2024; Clunes Pinochet, 2020; Dai et al., 2022; Ghafoor et al., 2021; Nakachew et al., 2024; Zhao et al., 2024). Conversely, incorrect nitrogen application, whether in rate or timing can exacerbate nitrate leaching and N_2O emissions, reducing both agronomic efficiency and environmental sustainability (Dai et al., 2022; Feyisa et al., 2024; Maharjan et al., 2014; Noor et al., 2023). Optimal nitrogen fertilization is particularly relevant in semi-arid Mediterranean systems, where water availability constrains nitrogen uptake and increases the risk of nitrogen losses (Pampana and Mariotti, 2021). Nitrogen management also directly influences grain quality, particularly protein content, which is closely regulated by nitrogen dynamics throughout the crop cycle. Mineral fertilisation and slow-release nitrogen fertilisation differ in their capacity to support nitrogen accumulation before anthesis or uptake after anthesis, and both processes play a key role in supporting grain protein deposition (Giunta et al., 2022). Therefore, fertilisation strategies that optimise nitrogen timing can simultaneously improve yield and quality, specifically under drought-prone conditions.

Organic fertilisation represents an alternative strategy that provides a sustained nitrogen supply by gradually releasing nitrogen through the mineralisation of organic matter, reducing nitrous oxide emissions (Tang et al., 2024), nitrogen leaching (Yang et al., 2021), and production costs, while supporting adequate grain yields in wheat cropping

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systems (Bilsborrow et al., 2013). However, the identification of wheat genotypes specifically adapted to low chemical input and organic farming systems remains limited, highlighting the need for targeted research to enhance the sustainability of these production systems (Iannucci and Codianni, 2016). In this context, ancient wheat varieties and local landraces represent valuable genetic resources for breeding programmes focused on organic and low-input agriculture, as these genotypes evolved over centuries through farmer selection under local environmental constraints, limited nutrient availability, and minimal chemical inputs, thereby developing enhanced tolerance to abiotic stresses and suboptimal agronomic conditions (Careddu et al., 2023; Newton et al., 2012; Thanopoulos et al., 2024). In Mediterranean environments, landraces and old varieties have shown superior adaptation to low soil moisture and nitrogen availability compared with modern varieties, achieving higher nitrogen uptake and utilisation efficiency (Lupini et al., 2021a). Despite these advantages limited information is available on how landraces and ancient wheat varieties respond to optimised nitrogen management strategies under Mediterranean conditions. Therefore, this study aims to evaluate the effectiveness of conventional, slow-release, and organic fertilisation strategies in improving grain yield, grain quality, and nitrogen apparent recovery efficiency (NARE) in durum wheat, by comparing modern varieties with ancient varieties and local landraces under contrasting nitrogen management regimes.

2. Materials and Methods

2.1. Experimental site description

The field experiment was conducted during the 2021–2022 and 2022–2023 growing seasons in southern Italy, at the experimental farm of the University of Catania, Sicily (37°24′ N, 15°03′ E, 10 m a.s.l.). The site is located within the Catania Plain and is characterised by a Xerofluvent soil (Table 1).

2.2. Climatic conditions

The local climate is classified as subtropical Mediterranean, with mild, rainy winters and hot, dry summers. Throughout the experiment, temperature patterns, rainfall, and reference evapotranspiration were consistent with typical Mediterranean conditions (Table 2, Figs. 1 and 2).

Table 1
Soil characteristics of the field site in the top layer (0–50 cm).

Soil characteristics	Unit	Value	Method
Sand	%	49.3	Gattorta; (Lotti and Galoppini, 1967)
Loam	%	22.4	Gattorta; (Lotti and Galoppini, 1967)
Clay	%	28.3	Gattorta; (Lotti and Galoppini, 1967)
pH		8.6	In water solution; (Baur and Ensminger, 1977)
Total calcareous	%	15.2	Gas-volumetric; (Baur and Ensminger, 1977)
Organic matter	%	1.4	Walkley and Black; (Baur and Ensminger, 1977)
Total *N*	‰	1	Kjeldahl; (Baur and Ensminger, 1977)
P_2O_5 availability	mg kg^{-1}	5	Ferrari; (Baur and Ensminger, 1977)
K_2O availability	mg kg^{-1}	245	Dirks and Scheffer; (Baur and Ensminger, 1977)
Bulk density	g cm^{-3}	1.1	
Field capacity at −0.03 MPa	%	27	
Wilting point at −1.5 MPa	%	11	

Table 2
Meteorological variables (Tmax = month average of daily maximum temperature, Tavg = month average of daily mean temperature, Tmin = month average of daily minimum temperature, ETo = month sum of daily reference evapotranspiration according to Allan et al. (1997), for 2021–2022 and 2022–2023 growing seasons and long-term averages at the experimental site (Catania, 37°24′ N., 15°03′ E., 10 m a.s.l.).

Variable	2021–2022 observed values	2022–2023 observed values	Long term average
Tmax	21.1 °C	20.8 °C	20.5 °C
Tmin	9.9 °C	10.0 °C	10.1 °C
Tavg	15.4 °C	15.5 °C	15.1 °C
ET0	588.0 mm	543.5 mm	586.8 mm
Precipitation October to July	835.4 mm	474.2 mm	544.1 mm
Precipitation Sowing to Harvesting	103.6 mm	303.4 mm	249.3 mm

Average air temperatures throughout the growing seasons (January to June) were slightly higher in 2022 than in 2023, with monthly mean temperatures of 15.5 °C and 15.3 °C, respectively. The monthly average of daily minimum temperatures during the growing seasons was 9.9 °C in 2022 and 10.0 °C in 2023, aligning with the long-term average of 10.0 °C. The monthly average of daily maximum temperatures was 21.0 °C in 2022 and 20.8 °C in 2023, both above the long-term average of 20.5 °C. Reference evapotranspiration was higher in the 2022 growing season (588.0 mm) than in 2023 (543.5 mm), which was below the long-term average (586.8 mm). Total precipitation from October 2021 to July 2022 (835.0 mm) was markedly higher than from October 2022 to July 2023 (474.0 mm), whereas the long-term average was 544.1 mm (Table 2). From sowing to harvest, precipitation was lower in 2022 (103.6 mm) than in 2023 (303.4 mm).

2.3. Experimental design

The experiment used a split-plot design with two factors (management and genotype) and three replicates. Management was assigned to the main plots, while genotype was assigned to the sub-plots. Each main plot measured 45 m^2 (6 m wide × 7.5 m long). The experimental unit (sub-plot) measured 1.5 m × 7.5 m (11.25 m^2).

2.4. Management factor

The management factor included five treatments: conventional management (C), two organic management systems (OR1 and OR2), conventional management with slow-release fertilisation (SRF), and a no-fertilisation treatment with conventional weed control (N0) (Table 4).

2.5. Genotype factor

The genotype factor comprised four durum wheat genotypes (Table 5): one Sicilian landrace (*Triticum turgidum* subsp. *durum* (Desf.), "*Russello Priziusa*"), one ancient variety ("*Senatore Cappelli*"), and two modern varieties ("*Core*" and "*Mongibello*").

2.6. Agronomic management

The seedbed was prepared after the first autumn rain using skim ploughing at a depth of 0.40 m, followed by disk harrowing. Sowing was carried out on 9 February 2022 and 4 January 2023, in the first and second growing seasons, respectively, using a self-propelled plot seeder (Vignoli Tartaro, Forlì, Italy). The sowing rate was 200 kg ha^{-1} , with seeds placed in rows 21 cm apart, comprising six rows, each 8 m long, to achieve approximately 350–400 plants m^{-2}. Harvesting was performed at full ripening on 12 July 2022 and 13 July 2023 using a plot combine

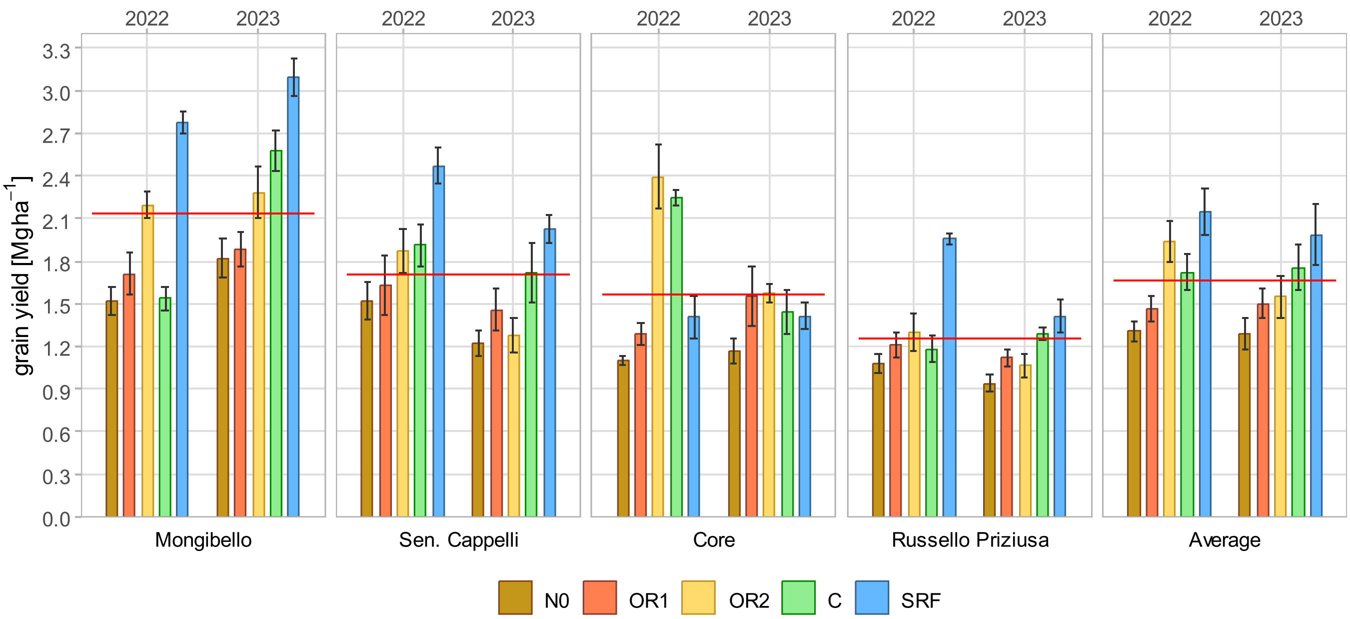

Fig. 1. Grain yield (Mg ha^{-1}) during the 2022 and 2023 cropping seasons under four management levels for four wheat genotypes. Red lines indicate genotype means. Error bars represent the standard error. Tukey's minimum significant difference (MSD) = 0.66 Mg ha^{-1} .

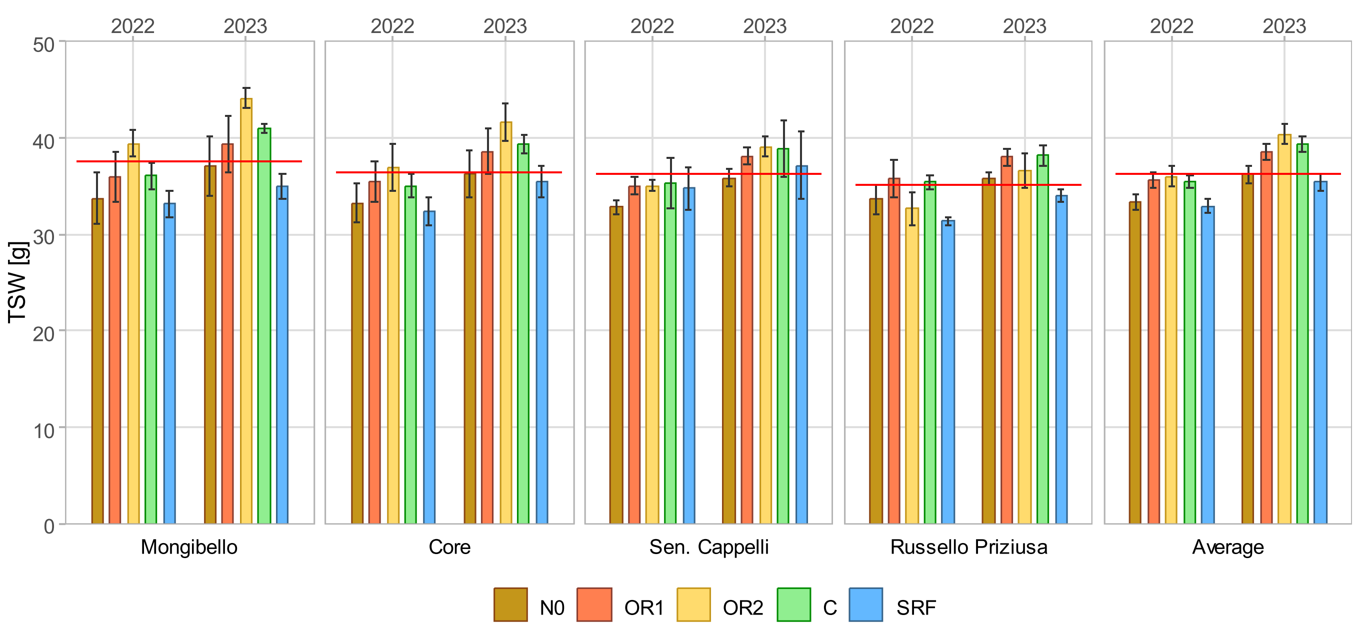

Fig. 2. Thousand-seed weight (TSW, g) during the 2022 and 2023 cropping seasons under four management levels for four wheat genotypes. Red lines indicate genotype means. Error bars represent the standard error. Tukey's minimum significant difference (MSD)= 4.95 g.

Table 4
Overview of the management factor levels applied in the study. The experiment included five management systems: conventional (C), two organic management approaches (OR1 and OR2), conventional management with slow-release fertilisation (SRF), and no-fertilisation with weed control (N0).

		Pre-sowing		Top dressing		Total
Conventional management (C)	N	54 kg ha^{-1}	(Ammonium sulphate, 21%)	26 kg ha^{-1}	Ammonium nitrate, 34%	80 kg ha^{-1}
	P	99 kg ha^{-1}	(Superphosphate, 19%)			99 kg ha^{-1}
Slow-release fertilisation (SRF)	N	80 kg ha^{-1}	(Polymer-coated urea, 46%)			80 kg ha^{-1}
	P	99 kg ha^{-1}	(Phosphoric anhydride, 19%)			99 kg ha^{-1}
Organic 1 management (OR1)	N	54 kg ha^{-1}	(Organic nitrogen, 5%)	26 kg ha^{-1}	Organic nitrogen, 7%	80 kg ha^{-1}
	P	108 kg ha^{-1}	(Phosphoric anhydride, 10%)			108 kg ha^{-1}
Organic 2 management (OR2)	N	54 kg ha^{-1}	(Organic nitrogen, 5%)	26 kg ha^{-1}	Organic nitrogen, 6%	80 kg ha^{-1}
	P	99 kg ha^{-1}	(Phosphoric anhydride, 10%)			99 kg ha^{-1}
No-fertilisation (N0)	N	0		0		0
	P	0		0		0

Table 5
Wheat varieties evaluated in the experiment, including detailed descriptions of the genotypes analysed.

Genotypes Name	Origin	Type	Pedigree
Russello Priziusa	Italy	Landrace	Sicilian native landrace
Senatore Cappelli	North African	Old variety	Strampelli's selection. North African landrace derived from Jennah Khetifa
Core	Italy	Variety	Platani x Gianni
Mongibello	Italy	Variety	Trinakria x Valforte

harvester (Wintersteiger, Ried, Austria).

2.7. Measurements

The main meteorological data (maximum and minimum air temperatures and rainfall) were recorded by an automatic weather station (Delta-T, WS-GP1 Compact) located near the experimental field. The occurrence of crop phenological phases was assessed visually on a weekly basis by recording the time when 50% of the culms in the sampled area (1×1 m^2) reached specific growth stages according to the Zadoks scale (Zadoks et al., 1974). The intervals between sowing and earing (GS0–GS6) and between earing and physiological maturity (GS6–GS9) were subsequently calculated.

Threshing was conducted using a wheat threshing machine (Haldrup, Ilshofen, Germany), allowing efficient separation of grain from plant residues. This procedure ensured the isolation of seeds for further analysis or processing, maintaining sample purity and minimising contamination from other plant parts. The amount of grain harvested from each subplot was weighed using an electronic scale and reported per unit area to calculate grain yield (Gy) at 13% moisture content. Plant height, measured from the stem base to the ear tip, was determined in the laboratory on a representative subsample of 100 plants collected from the secondary subplots.

A subsample of 1 kg of grain was collected from each subplot to measure the thousand-seed weight (TSW) using a seed counter on a 15 g grain sample. The white starchy kernel index (WS, %) was assessed through visual inspection on 30 g representative subsamples, following the procedure described by Spina et al. (2023).

The shrunken kernel index (SK, %) was assessed on a 30 g representative subsample by counting the number of kernels passing through a 1.8 mm $\times$ 20.0 mm oblong sieve, according to EN ISO 5223, excluding broken kernels.

Total nitrogen content of grain and aboveground biomass (AGB) was determined using the Kjeldahl method (Desai and Bhatia, 1978). Grain protein content (Gp) was calculated by multiplying Kjeldahl nitrogen by 5.75. Nitrogen apparent recovery efficiency (NARE) was calculated according to Duncan et al. (2018), based on nitrogen uptake determined by multiplying Kjeldahl nitrogen concentration by grain or AGB yield.

2.8. Statistical Analysis

The data were subjected to a mixed-model analysis of variance (three-way ANOVA) to assess the effects of management (fixed factor assigned to the main plot), genotype (fixed factor assigned to the subplot), and year (random factor) on grain yield, grain protein content, plant height, white starchy index (WS), shrunken kernels (SK), seed weight, the interval from sowing to earing (GS0–GS6), the interval from earing to physiological maturity (GS6–GS9), and nitrogen apparent recovery efficiency (NARE). The Shapiro–Wilk test was used to assess the normality of residuals, while the Bartlett test was applied to evaluate homoscedasticity. Tukey's Honestly Significant Difference (HSD) test, at a 95% confidence level, was performed to compare pairwise the means of genotype, management, and genotype $\times$ management interactions and calculate the Minimum Significant Difference (MSD). Correlations between variables were evaluated using Pearson's product–moment correlation test. All analyses were performed using R statistical software (R Core Team, 2021).

3. Results

3.1. Crop phenology

Management had no significant effect on the interval between sowing and earing (GS0–GS6), whereas genotype and year showed significant effects (Table 6). The GS0–GS6 intervals were longer in 2023 than in 2022 (111.7 and 104.6 days on average, respectively). Slow-release fertilisation (SRF) resulted in slightly longer intervals (109.2 days) than organic management 2 (OR2) (108.8 days), organic management 1 (OR1) (108.1 days), and conventional management (C) (107.7 days). The shortest duration was observed under no fertilisation (N0), with an average of 107 days. Among the genotypes, the durum wheat landrace *Russello Priziusa* (110.2 days) and *Senatore Cappelli* (110.0 days) exhibited the longest GS0–GS6 intervals, whereas *Mongibello* (107.5 days) and *Core* (104.9 days) showed shorter intervals (Table 7).

The interval from earing to physiological maturity (GS6–GS9) was also longer in 2023 (51.81 days on average) than in 2022 (26.68 days on average). Among the genotypes, the modern varieties *Core* and *Mongibello* exhibited the longest intervals (41.0 and 40.3 days, respectively), whereas the landrace *Russello Priziusa* and the ancient variety *Senatore Cappelli* showed shorter durations (38.3 and 37.4 days, respectively) (Table 7).

The interval from earing to physiological maturity (GS6–GS9) was also longer in 2023 (51.8 days on average) than in 2022 (26.7 days on average). Among the genotypes, the modern varieties *Core* and *Mongibello* exhibited the longest intervals (41.0 and 40.3 days, respectively), whereas the landrace *Russello Priziusa* and the ancient variety *Senatore Cappelli* showed shorter durations (38.3 and 37.4 days, respectively) (Table 7).

3.2. Morphologic and Productive Traits

3.2.1. Grain Yield

Grain yield was significantly affected by genotype, management, and their interaction (Table 6). The highest yields were achieved under slow-release fertilisation (SRF) (2.06 Mg ha^{-1}, on average), whereas the lowest yields were observed under no fertilisation (N0) (1.30 Mg ha^{-1}, on average) (Table 7). Among the genotypes, *Mongibello* achieved the highest grain yield (2.13 Mg ha^{-1}, averaged across treatments), whereas *Russello Priziusa* showed the lowest yield (1.25 Mg ha^{-1}, averaged across treatments) (Table 7, Fig. 1). Both *Mongibello* and *Senatore Cappelli* responded positively to SRF, whereas *Core* performed better under conventional fertilisation. Both modern varieties performed well under the OR2 organic management.

3.2.2. Thousand-seed weight (TSW)

Genotype, year, and the management $\times$ genotype interaction significantly affected thousand-seed weight (TSW), whereas management alone had no significant effect (Table 6). The modern varieties *Mongibello* and *Core* exhibited the highest TSW values (37.5 g and 36.4 g, respectively) and showed greater variability than the landrace and ancient variety, producing heavier kernels under OR2 and lighter kernels under SRF (Table 7). Lower TSW values were recorded for *Senatore Cappelli* (36.2 g) and *Russello Priziusa* (35.2 g), with limited variation across management systems (Table 7).

3.2.3. Plant Height

Genotype, year, and management significantly affected plant height, whereas the management $\times$ genotype interaction was not significant (Table 6). Plant height was greater in 2023 (93.78 cm) than in 2022 (80.85 cm). Organic management systems (OR1 and OR2) resulted in

Table 6
Three-way ANOVA for main effects (management, genotype, year) and their interaction (management × genotype) on grain yield, grain protein content, nitrogen apparent recovery efficiency (NARE), plant height, white starchy index (WS), shrunken kernels (SK), thousand-seed weight (TSW), interval sowing–earing (GS0–GS6), and interval earing–physiological maturity (GS6–GS9). P-values are reported for fixed factors and interactions, while mean square errors are reported for main-plot and subplot errors.

Source of Variation	Year	Main plot variance			Subplot variance		
		Management	Block	Main plot error	Genotype	Management x Genotype	Subplot error
Degrees of freedom	1	4	2	8	3	12	89
Grain Yield	0.078	1.63×10^{-6}	0.572	0.046	$< 2 \times 10^{-16}$	3.75×10^{-5}	0.10
Protein content	1.53×10^{-3}	0.059	0.911	1.53	4.30×10^{-3}	0.663	0.47
NARE	0.157	2.50 × 10–5	0.514	0.0074	0.027	7.09×10^{-6}	0.0073
Plant Height	$< 2.2 \times 10^{-16}$	0.025	0.062	51.2	$< 2 \times 10^{-16}$	0.821	41.0
SK	0.348	0.098	0.058	938	2.38×10^{-5}	5.06×10^{-4}	127
WS	0.002507	0.00272	0.52281	82.1	$< 2 \times 10^{-16}$	$< 2 \times 10^{-16}$	4.89
TSW	5.385×10^{-9}	0.116	0.292	28.0	0.00284	0.02988	5.52
S-E (GS0-GS6)	$< 2.2 \times 10^{-16}$	0.368	0.197	9.19	1.44×10^{-10}	0.989	8.6
E-PM (GS6-GS9)	$< 2.2 \times 10^{-16}$	0.393	0.163	10.3	1.78×10^{-8}	0.971	5.2

Table 7
Mean values (± standard errors) of grain yield, grain protein content, nitrogen apparent recovery efficiency (NARE), plant height, white starchy index (WS), shrunken kernels (SK), thousand-seed weight (TSW), interval sowing–earing (GS0–GS6), and interval earing–physiological maturity (GS6–GS9) for the experimental factors genotype and management. Different letters indicate significant differences according to Tukey's HSD test (p ≤ 0.05).

		Protein content (%)	Plant height (cm)	GS0-GS6 (days)	GS6-GS9 (days)
Variety	*Russello Priziusa*	12.96 ± 0.16 b	111.7 ± 1.9 a	110.2 ± 1.0 a	38.3 ± 2.2 b
	Senatore Cappelli	13.59 ± 0.15 a	112.9 ± 1.5 a	110.0 ± 1.0 a	37.4 ± 2.4 b
	Core	13.10 ± 0.15 b	67.3 ± 1.4 b	104.9 ± 0.8c	41.0 ± 2.4 a
	Mongibello	13.26 ± 0.18 ab	57.5 ± 2.2 c	107.5 ± 0.5 b	40.3 ± 2.5 a
Management	N0	12.40 ± 0.09	82.7 ± 5.3 b	107.0 ± 1.0	40.5 ± 2.7
	OR1	13.38 ± 0.13	90.8 ± 5.4 a	108.1 ± 1.1	39.5 ± 2.7
	OR2	13.32 ± 0.19	90.2 ± 5.8 a	108.8 ± 1.0	38.4 ± 2.7
	C	13.38 ± 0.18	87.0 ± 5.7 ab	107.7 ± 0.9	39.7 ± 2.7
	SRF	13.65 ± 0.18	86.0 ± 5.6 ab	109.2 ± 1.1	38.1 ± 2.6

taller plants than conventional management or SRF (90.8, 90.2, 87.0, and 86.0 cm, respectively) (Table 7). The N0 treatment produced the shortest plants (82.1 cm). *Senatore Cappelli* (112.9 cm) and *Russello Priziusa* (111.6 cm) were significantly taller than the modern varieties *Core* (67.3 cm) and *Mongibello* (57.5 cm) (Table 7).

3.3. Quality traits

3.3.1. Protein Content

Grain protein content was significantly affected by genotype and year, whereas management and the management × genotype interaction had no significant effects (Table 6). Protein content was higher in 2023 than in 2022 (13.4% vs. 13.0%), likely due to the longer growing cycle (Table 7). *Senatore Cappelli* showed the highest protein content (13.6%), followed by *Mongibello* (13.3%), while *Core* and *Russello Priziusa* exhibited protein contents of 13.0% and 13.1%, respectively (Table 7).

3.3.2. White Starchy (WS) index

The white starchy (WS) index was significantly affected by management, genotype, year, and the management × genotype interaction (Table 6). White starchy values were higher in 2022 than in 2023 (12.3% and 10.4%, respectively). Slow-release fertilisation resulted in the lowest WS incidence (5.38%, on average), whereas the highest WS values were observed under N0 (20.6%) (Table 7). *Core* exhibited the highest WS value among genotypes (20.4%), followed by *Senatore Cappelli*, *Russello Priziusa*, and *Mongibello* (9.4%, 8.8%, and 6.9%, respectively) (Table 7; Fig. 3). *Mongibello* maintained a low WS incidence even under reduced nitrogen input, whereas the other genotypes were more affected by low nitrogen availability, particularly under N0 and OR1 (Fig. 3).

3.3.3. Shrunken Kernels (SK)

The proportion of shrunken kernels (SK) was significantly affected by genotype and the management × genotype interaction, whereas management alone had no significant effect (Table 6). The N0 treatment resulted in the lowest SK incidence (39.1%, averaged across genotypes), whereas fertilised treatments exhibited higher SK values (Table 7). The SRF treatment produced the highest SK incidence (65.5%, on average), compared with C, OR1, and OR2 (45.9%, 42.9%, and 42.3%, respectively) (Table 7). Among the genotypes, *Core* exhibited the lowest SK values (38.6%, on average). *Senatore Cappelli* showed the lowest variability across management systems, whereas *Core* maintained low SK values across treatments, except under SRF (Fig. 4).

3.3.4. Nitrogen Apparent Recovery Efficiency (NARE)

Nitrogen apparent recovery efficiency (NARE) was significantly affected by year, management, and genotype, whereas the management × genotype interaction was not significant (Table 6). Nitrogen apparent recovery efficiency was highest under SRF (29.5%, on average), followed by OR2 (18.2%) and conventional management (17.0%). The OR1 treatment resulted in the lowest NARE (8.5%) (Table 7). Among genotypes, *Mongibello* and *Senatore Cappelli* exhibited the highest NARE (22.1% and 19.1%, respectively), whereas *Russello Priziusa* showed the lowest efficiency (13.6%). *Mongibello*, *Senatore Cappelli*, and *Russello Priziusa* achieved their highest NARE under SRF, whereas *Core* performed better under OR2 and conventional management (Fig. 5).

3.3.5. Correlation between variables

Pearson correlation coefficients ≥ 0.20 or ≤ −0.20 were considered significant at the 95% confidence level (two-tailed test). A strong positive correlation was observed between grain yield and NARE (r = 0.84) and between grain protein content and NARE (r = 0.32). Consequently, NARE was negatively correlated with WS (r = −0.35). Grain yield was negatively correlated with plant height (r = −0.35) and with the WS index (r = −0.32) (Fig. 6). Grain protein content was positively correlated with the duration of GS0–GS6 (r = 0.31), GS6–GS9 (r = 0.20), and SK (r = 0.22), while showing a negative correlation with WS (r = −0.39). Plant height was positively correlated with GS0–GS6

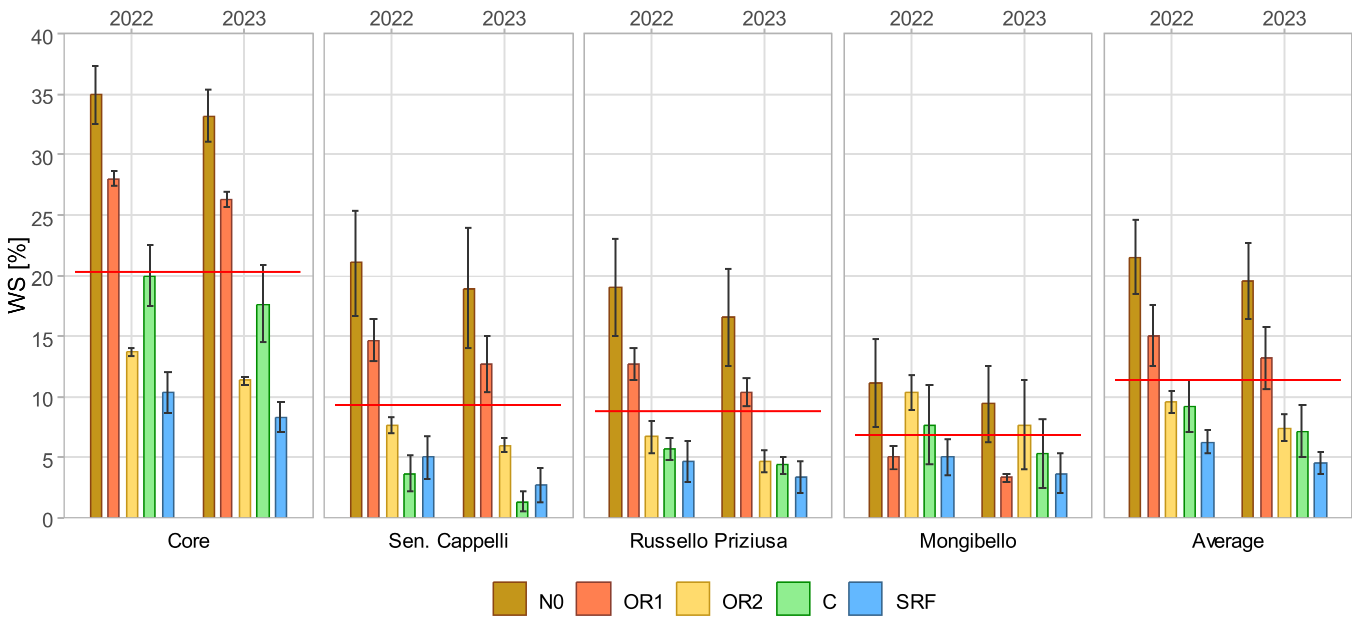

Fig. 3. White starchy index (WS, %) during the 2022 and 2023 cropping seasons under four management levels for four wheat genotypes. Red lines indicate genotype means. Error bars represent the standard error. Tukey's minimum significant difference (MSD)= 4.67%.

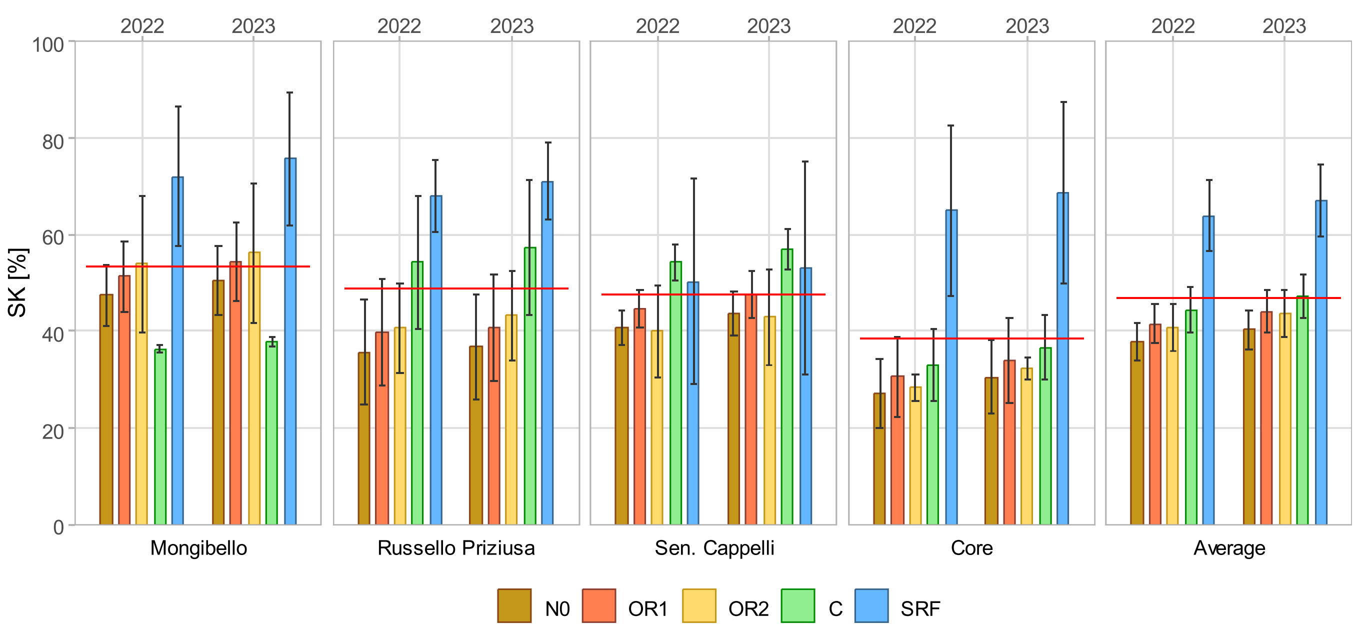

Fig. 4. Shrunken kernels (SK, %) during the 2022 and 2023 cropping seasons under four management levels for four wheat genotypes. Red lines indicate genotype means. Error bars represent the standard error. Tukey's minimum significant difference (MSD)= 23.8%.

(r = 0.48) and negatively correlated with WS (r = −0.22). Kernel weight was positively correlated with GS6–GS9 (r = 0.48) and negatively correlated with SK (r = −0.35). The GS0–GS6 interval was positively correlated with GS6–GS9 (r = 0.56) and SK (r = 0.28), and negatively correlated with WS (r = −0.36). WS and SK were strongly negatively correlated (r = −0.54).

4. Discussion

This study evaluated the impact of various agronomic management practices, including conventional fertilisation, slow-release nitrogen fertilisation, and organic farming, on the productivity, grain quality, and nitrogen apparent recovery efficiency (NARE) of selected durum wheat landraces and modern varieties under Mediterranean drought-prone conditions. The selection of organic and slow-release nitrogen fertilisers was primarily driven by the need to ensure adequate nitrogen uptake by wheat grown in the Mediterranean climate, which is frequently affected by irregular rainfall and prolonged dry periods. Under these conditions, conventional nitrogen fertilisation strategies may result in low efficiency due to limited plant uptake and increased leaching losses (Savin et al., 2019; Tita et al., 2025).

The differing responses of landraces and ancient varieties to organic and slow-release nitrogen fertilisation strategies, in contrast to modern varieties, are mainly attributed to differences in growth cycle length (Carranza-Gallego et al., 2019; Royo et al., 2020). Ancient landraces and varieties generally exhibit longer vegetative phases, allowing greater flexibility in utilising slow-release nitrogen sources (Ayadi et al., 2016; Zhou et al., 2022), whereas modern varieties, bred for shorter cycles,

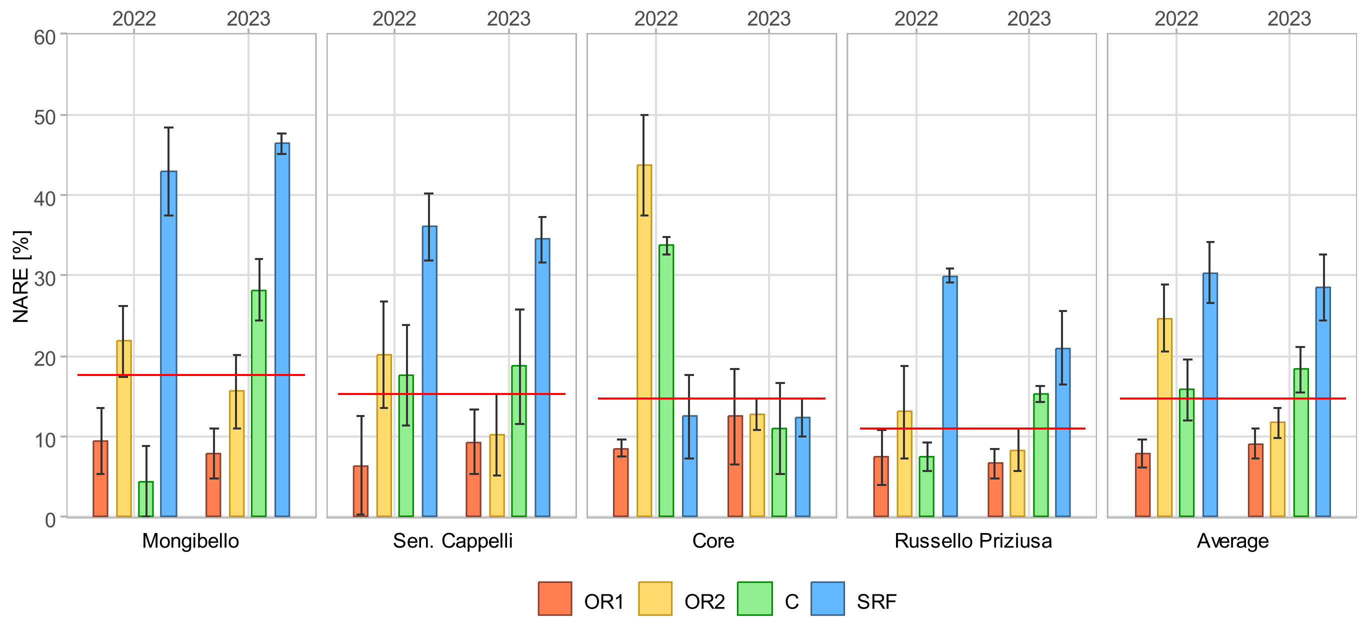

Fig. 5. Nitrogen apparent recovery efficiency (NARE, %) during the 2022 and 2023 cropping seasons under four management levels for four wheat genotypes. Red lines indicate genotype means. Error bars represent the standard error. Tukey's minimum significant difference (MSD)= 19.3%.

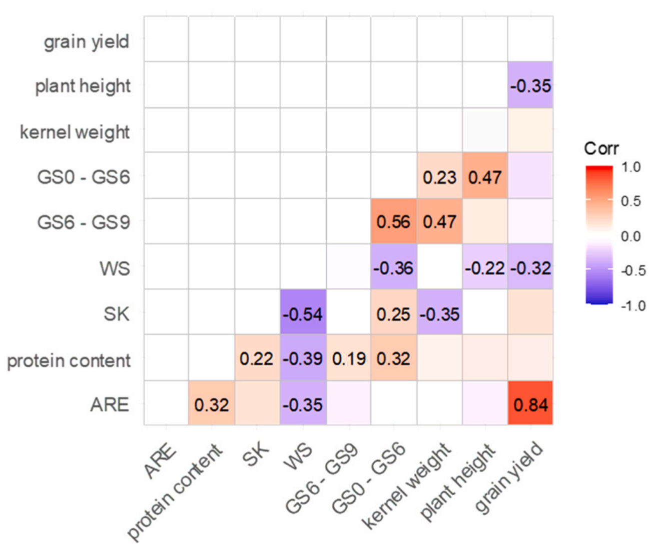

Fig. 6. Pearson correlation matrix of the measured variables (grain yield, protein content, SK = Shrunken Kernels, WS = White Starchy Index, plant height, kernel weight, GSO – GS6 = length of the interval between sowing to anthesis, GS6 - GS9 = length of the interval between anthesis to seed ripening and NARE = Nitrogen Apparent recovery efficiency). Correlation coefficients ≥ 0.20 or ≤ −0.20 are significant at a 95% confidence level in a two-tailed test).

may not fully capitalise on late nitrogen availability (Lammerts van Bueren and Struik, 2017; Lynch et al., 2023). This suggests that optimising fertilisation requires an integrated approach that considers varietal phenology and synchronisation between nutrient supply and crop demand (Liang et al., 2023).

In this study, differences were observed in the length of the sowing-to-heading and heading-to-maturity intervals across the two years of experimentation. These variations were primarily driven by higher temperatures during the growing season in the first year, resulting from late sowing caused by extreme rainfall during the previous autumn. Neither the sowing-to-earing nor the earing-to-maturity interval was significantly affected by management practices, although the latter was slightly shorter under delayed nitrogen availability, likely due to increased water consumption associated with greater plant growth. Previous studies have reported similar findings, demonstrating that nitrogen availability has no effect on the duration of the grain-filling phase (Ercoli et al., 2008). Landraces exhibited a delayed earing phase compared to modern varieties, in agreement with previous results (Motzo and Giunta, 2007). This trait may increase their susceptibility to drought and heat stress during the late growing season (Soriano et al., 2018).

Longer sowing-to-heading and heading-to-maturity intervals are generally associated with higher grain yields under optimal or moderately limiting conditions, due to extended leaf area duration and prolonged photosynthetic assimilation (Bożek et al., 2021; Corinzia et al., 2024). Conversely, shortening of the phenological cycle negatively impacts productivity, as wheat requires sufficient time for photosynthate accumulation and grain filling. In the present study, grain yield was not significantly correlated with either sowing-to-heading or heading-to-maturity intervals. This result can be attributed to high temperature and drought stress during the late grain-filling phase, which favoured early-ripening genotypes, as reported by Cosentino et al. (2019). Previous studies have shown that grain yield is sink-limited, being strongly influenced by environmental and agronomic constraints during floret development, when floret abortion can reduce the number of grains per spike (Ferrante et al., 2010), and during grain filling, when heat and drought stress reduce the translocation of photosynthates produced between emergence and earing (Acevedo et al., 2002; Djouadi et al., 2021).

Delayed wheat sowing can be adopted in Mediterranean environments in response to conditions that hinder agronomic operations during the sowing period, particularly unsuitable soil moisture (Bassu et al., 2009, Bussay et al., 2023, Gomez-Macpherson and Richards, 1995, Mahdi et al., 1998). However, delayed sowing causes shortening of phenological phases and increases the likelihood of adverse climatic conditions during vegetative growth and grain filling. This leads to lower biomass accumulation and grain production (Lopes et al., 2018; Shah et al., 2020; Tita et al., 2025), reduced nitrogen use efficiency (Liu et al., 2021), and lower competitiveness against weeds (Beres et al., 2020). Conversely, delayed sowing can be beneficial for ancient landraces by enhancing lodging resistance through reduced culm height and increased tensile strength of the basal internode (Liu et al., 2021). The present study reflects the effects of delayed sowing caused by excessive (2021–2022) or insufficient (2022–2023) soil moisture, which resulted in shortened phenological phases and below-average grain yields. Shorter phenological phases, particularly during grain filling, limit biomass accumulation while concentrating nitrogen uptake in the grains, thereby enhancing grain protein content and intensifying the yield–protein trade-off (Jarecki, 2024; Singh et al., 2012).

In this study, SRF increased grain yield by 19.0% compared to mineral fertilisers and 18.6% compared to organic fertilisation (OR2), in agreement with the 21% yield increase reported by Amine et al. (2023). That study also reported that slow-release fertilisers significantly improved key agronomic traits, including tillering, number of ears per plant, and canopy height, compared to fast-release mineral fertilisers. Similarly, Ghafoor et al. (2022) reported that controlled-release fertilisers positively affect wheat productivity, improve water use efficiency, and enhance grain nutritional quality, contributing to more sustainable resource management.

Anastasi et al. (2019) further demonstrated that the yield gap between organic and conventional management is more pronounced in modern varieties than in local landraces or ancient varieties, in agreement with the present study. These local genotypes were developed through breeding and selection under low-input systems, without chemical weed control or mineral fertilisers, making them better adapted to marginal environments (Devilliers et al., 2023).

In the present study, slow-release fertilisation (SRF) increased both grain yield and total protein yield, indicating an overall improvement in nitrogen uptake and utilisation efficiency. However, grain protein concentration was not significantly affected by SRF, a response that is likely attributable to a protein dilution effect, whereby increased carbohydrate accumulation associated with higher biomass and grain yield offsets gains in nitrogen accumulation (Bogard et al., 2010). Durum wheat varieties differ in their nitrogen accumulation strategies: a gradual nitrogen supply, such as that provided by SRF or organic fertilisation, favours genotypes with greater post-anthesis nitrogen uptake capacity, particularly ancient landraces, which tend to absorb nitrogen later in their phenological development (Lupini et al., 2021b). The positive effects of SRF on grain protein content are more evident in arid or climatically erratic environments, where fluctuations in soil moisture increase nitrogen losses through leaching or volatilisation (Wang et al., 2021). Conversely, organic fertilisation, while beneficial for long-term soil health, may not satisfy immediate crop nitrogen demand during early growth stages, often resulting in lower grain protein concentrations (Scandurra et al., 2024).

The relationship between grain yield and protein content frequently reflects a trade-off, as yield increases may dilute protein concentration (Brill et al., 2012; Terman et al., 1969). Interestingly, this study detected a slight positive correlation between grain yield and protein content under higher nitrogen availability, suggesting that enhanced nitrogen supply supported both traits. Nevertheless, the effect of fertilisation management on protein content was not statistically significant, as no differences were observed among SRF, conventional, or organic treatments, except for N0, which resulted in significantly lower protein levels. One possible explanation is that SRF moderated protein dilution by improving nitrogen assimilation efficiency (Martre et al., 2015). Previous studies have reported significantly higher protein content under SRF compared to conventional or organic management (Shoukat et al., 2023; Zeidan and El Kramany, 2005). Plant height was primarily determined by the amount of nitrogen applied, with limited influence from fertilisation type. This finding supports results by Ghafoor et al. (2022), who reported that nitrogen source does not significantly affect plant height, indicating that crop nitrogen requirements were equally met up to earing.

Thousand-seed weight (TSW) is a key indicator of wheat productivity and quality, influencing milling performance. Stress conditions such as drought and high temperatures negatively affect kernel development, leading to shrunken kernels (OlaOlorun et al., 2021) or poor starch accumulation (Filip et al., 2023), and consequently lower TSW. Nitrogen mismanagement exacerbates these effects, whereas continuous nitrogen availability promotes optimal kernel development (Derebe et al., 2022; Godebo et al., 2021; Kubar et al., 2022). However, in this study, SRF reduced TSW due to increased kernel number per spike, which resulted in insufficient grain filling and a higher incidence of shrunken kernels. Conversely, higher TSW values were observed under OR2, conventional, and OR1 management, consistent with previous findings (Shoukat et al., 2023; Zhou et al., 2022).

The effects of fertilisation management on TSW and shrunken kernel (SK) incidence varied among genotypes. Landraces exhibited lower variability across treatments than modern varieties, likely due to their greater capacity to translocate pre-anthesis assimilates, as reported for southern Mediterranean landraces (Moragues et al., 2006). Genotypic variation plays a critical role in kernel quality under stress conditions, with genotypes exhibiting better water retention and kernel hardness being less prone to shrinkage (Derebe et al., 2022; Guzmán et al., 2022). Among the tested varieties, the modern cultivar *Core* was the least susceptible to kernel shrinkage. Low soil nitrogen availability can result in white starchy kernels, negatively affecting the nutritional and processing quality of wheat (Kim and Kim, 2021). The present study confirmed a negative correlation between the white starchy index and grain protein content, with the highest incidence of white starchy kernels observed under N0 management.

The mismatch between soil nitrogen availability and crop nitrogen demand not only compromises yield and quality, but also increases environmental risks through nitrate leaching and emissions of ammonia and nitrous oxide due to volatilisation and denitrification (Zhang et al., 2022). These risks are exacerbated under late sowing conditions, which reduce nitrogen uptake efficiency (Ehdaie and Waines, 2001; Ferrise et al., 2010). Organic fertilisation and SRF enhanced nitrogen recovery efficiency by better aligning nitrogen availability with crop demand throughout the growing season. This result is consistent with findings by Govindasamy et al. (2023) and Yokamo et al. (2023), who reported improvements in NARE with slow-release nitrogen application. Nitrogen uptake is generally higher in high yielding and high protein genotypes (Abiola et al., 2024; Ierna et al., 2016; Lupini et al., 2021a; Mariem et al., 2020). Notably, local landraces and ancient varieties exhibited more stable performance across management strategies and higher nitrogen recovery when late nitrogen availability was ensured, consistent with reports of high post-anthesis nitrogen uptake in these genotypes (Lupini et al., 2021a). Under severe water stress, such as that typical of Mediterranean environments, the benefits of enhanced nitrogen use efficiency may be partially masked, reducing observable genetic differences between landraces and modern varieties. Nevertheless, modern genotypes demonstrated a greater ability to cope with combined water and nitrogen limitations by maintaining higher nitrogen use efficiency (Benchelali et al., 2022; Lupini et al., 2021a).

Overall, the results indicate that slow-release fertilisation (SRF) represents the most effective nitrogen management strategy under Mediterranean drought-prone conditions, as it ensures a continuous nitrogen supply aligned with crop uptake. This approach improves grain yield and nitrogen recovery efficiency while reducing environmental losses. Fast-release mineral fertilisation may induce nitrogen imbalances, particularly in ancient varieties and landraces longer growth cycles and higher late nitrogen demand, whereas it remains more suitable for modern varieties, which are selected for shorter phenological cycles and benefit from early nitrogen availability. Organic management showed comparable effectiveness to mineral fertilisation by compensating for lower early nitrogen availability with prolonged nutrient release. Nitrogen management becomes especially critical under delayed sowing conditions, which shorten the crop cycle and require fertilisation strategies capable of adapting to shorter phenological windows.

5. Conclusions

This study highlights the impact of various nitrogen fertilisation management practices on durum wheat phenology, grain yield, grain quality, and nitrogen apparent recovery efficiency in the Mediterranean area, by evaluating modern varieties, an ancient variety, and a local landrace. Climate variability in the Mediterranean region, particularly erratic precipitation patterns, leads to reduced wheat productivity and increases the risk of nitrogen losses. Extending the period of nitrogen availability to the crop, through slow-release nitrogen fertilisation and organic fertilisation, reduced yield fluctuations associated with limited soil water availability and enhanced soil nitrogen recovery. This minimised the risk of environmental pollution due to higher nitrogen apparent recovery efficiency. Among the evaluated strategies, slow-release fertilizers (SRF) proved to be the most effective management option, improving grain yield and nitrogen recovery efficiency by better synchronising nitrogen availability with crop demand, while simultaneously reducing environmental risks such as leaching and volatilisation. Organic fertilisation showed lower effectiveness under water-limiting conditions, particularly for modern varieties, due to insufficient early nitrogen availability. The study demonstrated that the ancient variety and the landrace, characterised by longer growth cycles and delayed nitrogen uptake, responded more positively to SRF and organic fertilisation, enhancing their resilience in marginal and drought-prone environments. Conversely, modern varieties, with shorter phenological cycles and higher early nitrogen requirements, benefited more from the slower release of nitrogen. Overall, the results indicate that nitrogen management strategies should be variety-specific, taking into account phenological development and nitrogen uptake dynamics to maximise productivity and grain quality while ensuring efficient resource use under the increasingly erratic precipitation patterns characteristic of the Mediterranean climate. This research provides valuable insights into the development of more sustainable wheat production systems, highlighting the potential role of landraces and ancient varieties within modern agricultural contexts.

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CRediT authorship contribution statement

Alessio Scandurra: Writing – original draft, Visualization, Investigation, Formal analysis. **Sebastiano Andrea Corinzia:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Salvatore Luciano Cosentino:** Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Giorgio Testa:** Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors 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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