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REGISTRATION

Cultivar

'Nachit', a wild-relative-derived durum wheat resilient to climate change in Morocco

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Abstract

Morocco, in North Africa, is a country vastly exposed to the whims of climate change, with frequent moisture and heat stresses occurring throughout the season. Hence, developing climate-resilient, high-yielding, and nutritious cultivars of durum wheat [*Triticum turgidum* L. *durum* (Desf.)] is a major goal and challenge of Moroccan crop breeders. In that sense, the exploitation of crop wild relatives (CWRs) holds great potential to increase genetic diversity for critical adaptation traits. 'Nachit' (Reg. no. CV-1202, PI 702365) is a CWR-derived durum wheat cultivar released in 2018 for cultivation in Morocco by a joint effort of the National Institute of Agronomic Research, Morocco and the International Center for Agricultural Research in the Dry Areas. Nachit was released due to its good adaptation to the Moroccan dry conditions combined with high yield potential under irrigated conditions, extremely large grains, and richness in protein content. It also combines several traits for drought tolerance such as earliness and deep root system. Nachit was derived from a top cross between two elite lines and a wild emmer [*T. turgidum* ssp. *dicoccoides*] collected in Syria. Hence, it provides a substantial example of exploitation of CWRs to achieve a superior cultivar adapted to the climatic stresses and responding to human needs.

1 | INTRODUCTION

Durum wheat [*Triticum turgidum* L. *durum* (Desf.) $2n = 4x = 28$. AABB] is an important crop cultivated in the Mediterranean basin (Bassi and Sanchez-Garcia, 2017; Sall et al, 2019). In Morocco, it is one of the oldest cultivated cereal species, consumed mainly as bread, couscous, and other traditional products. Durum wheat covers annually close to 1.0 million ha, with an average consumption of around 90 kg per person per year (Taghouti et al., 2019).

Abbreviations: INRA, National Institute of Agronomic Research; ICARDA, International Center for Agricultural Research in the Dry Areas; CWR, crop wild relative.

Morocco experiences strong effects of climate change, with frequent unseasonable high temperatures and altered timing and pattern of rainfall. These climatic factors are negatively affecting annual durum wheat productions, reducing farmer's income and exposing the population to food insecurity. Moroccan breeders have taken on this challenge and prioritized the development and delivery of new cultivars capable of withstanding the climatic stresses, while ensuring top yield potential and nutritious harvests suitable for human consumption. To achieve this goal, the narrow genetic base of modern cultivars has proven insufficient to identify truly tolerant genotypes. Instead, the use of broader crosses integrating wild plant species has been proposed by many authors as strategic to ensure sufficient genetic diversity to identify adapted types (Sall et al. 2018; Bassi & Nachit, 2019; Alhamad et al., 2020; Mazzucotelli et al., 2020; El Haddad et al., 2021a). Crop wild relatives (CWRs) are ideal sources of useful diversity since they have not undergone human selection and hence have been able to naturally thrive in extremely harsh environments (Maxted et al., 2010; El Haddad et al., 2021b; Sharma et al., 2021). Utilization of CWRs as a source of tolerance to multiple biotic and abiotic stresses has been successful in certain food crops of importance such as rice (*Oryza sativa* L.), cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] (Mammadov et al., 2018; El Haddad et al., 2021b; Sharma et al., 2021). For wheat, CWRs often exhibit better adaptation to stressful climatic conditions (Trethowan & Mujeeb-Kazi, 2008) and harbor more diverse genes for stress tolerance (Reynolds et al., 2007; Van Ginkel & Ogbonnaya, 2007; Sall et al., 2018; El Haddad et al., 2021a, 2021b).

Among the CWRs of wheat, wild emmer [*Triticum turgidum* ssp. *dicoccoides*, 2n = 4x = 28] comprises a rich reservoir of valuable alleles. In fact, *T. dicoccoides* carries many useful genes associated with many agronomic traits, abiotic and biotic stresses tolerances, grain protein content, and micronutrient mineral concentrations (Peng et al., 2013; Nevo, 2014; Sall et al., 2018; Bassi & Nachit, 2019; Alahmad et al., 2020; Mazzucotelli et al., 2020).

The objective of this study is to present 'Nachit' (Reg. no. CV-1202, PI 702365), a new CWR-derived durum wheat cultivar released in Morocco in 2018 thanks to its adaptation to both dry and irrigated conditions, with high protein content and large grains. Nachit was released jointly by the National Institute of Agronomic Research, Morocco (INRA) and the International Center for Agricultural Research in the Dry Areas (ICARDA). The name *Nachit* was selected in honor of Dr. Miloudi Nachit, a Moroccan researcher who retired in 2016 after more than 30 years devoted to durum wheat improvement at ICARDA, pioneering the use of CWRs and landraces for adaptation to climatic stresses.

Core Ideas

- Developing climate-resilient, high-yielding, and nutritious varieties for sustainable production is a challenge.
- The use of crop wild relatives is a promising approach to enhance genetic diversity of cultivated crops.
- Nachit durum wheat successfully incorporates high protein content and several traits for drought tolerance from crop wild relatives.
- Nachit shows good adaptation to Moroccan dry conditions.
- Nachit seed is available for research purposes or to develop new germplasm.

2 | METHODS

2.1 | The pedigree of Nachit

Nachit is the result of a cross-carried out by the ICARDA gene bank team, which involved the elite line 'Amedakul 1', known for its wide adaptation, and a *T. dicoccoides* accession collected from Syria, known for its large grain size. The resulting F_1 progenies were top-crossed to a second elite line 'Loukos', known for its top yield potential. The final pedigree is then Amedakul 1/T. dicoccoides Syrian collection // Loukos.

2.2 | The selection history of Nachit

The full recorded history is ICJMC04-001-0TH-0STH-0TH-0STH-14TH-0STH-0MCH-0MCH-030MCH-0MCH. The cross code stands for IC, ICARDA; J, genebank; MC, Mediterranean climates; and 04, completed in 2004. The specific cross was number 001 of that year. The F_1 progenies were then grown at Tel Hadya station (36˚40′ N, 37˚20′ E) in Aleppo (TH), Syria and bulk seeds were harvested (i.e., 0TH). The F_2 seeds were planted as twin rows in summer at the same station (STH) and bulk harvested (i.e., 0STH). The bulk $F_{1:2}$ seeds were then passed onto the breeding team of ICARDA that repeated the process to $F_{1:3}$ and then to $F_{1:4}$ using the same station in winter (0TH). The 5-m^2 plot of $F_{1:5}$ was then planted in the main season of Tel Hadya station and plant no. 14 was harvested (i.e., 14TH). A F_6 plant to row was planted in the summer off-season of the same station (0STH) and the whole row was bulk harvested. Two rounds of replicated yield trials were then conducted as $F_{6:7}$ and $F_{6:8}$ at the Moroccan station of Marchouch (0MCH, 33˚60′ N, 6˚7′ W) as part of the joint INRA–ICARDA trials. While more trials were conducted across Moroccan locations to confirm the performances of the entry, a set of 100 F_9 spikes were planted into rows at the station of Marchouch and 30 visually identical ones were bulk harvested (030MCH). This set was further multiplied (0MCH) to generate 25 kg of $F_{9:11}$ pure seeds and 300 F_{11} homogenous spikes needed for submission to the Moroccan catalogue.

After 2 years of multi-location testing, the Moroccan catalogue officially recognized this candidate as superior to the used checks and it was officially released as a cultivar in 2018. Following its release, 1000 spikes-to-row were planted

TABLE 1 Registration date of Nachit and seven durum wheat checks.

Cultivar	Registration date
Marzak	1984
Karim	1985
Amria	2003
Chaoui	2003
Irden	2003
Marouane	2003
Hamadi	2017
Nachit	2018

Source: INRA (2022).

at Marchouch to generate Generation 1 (G_1) in 2021, which was certified by Office National de Sécurité Sanitaire des Produits Alimentaires (ONSSA). Nachit has now been advanced to G_2 and following generations for commercial use.

2.3 | Traits and performance

In parallel to the national catalogue evaluation, a multi-year and multi-location experiment was conducted to further confirm the value of the cultivar Nachit. The results from 10 environments are presented here, defined as year × location combinations during two consecutive growing seasons, 2017–2018 and 2018–2019. The multi-environmental trials included seven Moroccan registered durum wheat cultivars as checks (Table 1).

The experiment was conducted at seven INRA experimental locations covering the four major agroecological zones of Moroccan wheat-producing regions (Table 2). The experiment was arranged in a randomized block design with three replications in plots of 9 m^2, of which 6 m^2 were harvested to assess grain yield. The agronomic management used followed best practice recommendations at each site.

Gain yield was expressed as tonnes per hectare, calculated by dividing the harvested weight of grains expressed in t by the 6-m^2 surface of the plots, and then multiplying this value by 10,000 m^2 to reach the surface of 1 ha. From the harvest, 200 g of seed for each genotype was analyzed for grain protein content using a Chopin Technologies Infraneo near-infrared spectroscopy. The characteristics of the monochromatic light ray which pass through the sample are compared to a predefined database to determine the amount of protein in grains. The 1000-kernel weight was determined by counting 300 randomly selected grains on a Numigral counter followed by weighting on a precision scale. Grain vitreousness was determined visually by counting the number of vitreous grains or after cutting grains. Whole grain flour samples were obtained with a whole mill grinder (Udy-Cyclone 0.5-mm sieve) and were used to determine yellow pigment index as b* value read on a chroma meter Konica Minolta CR-400.

2.4 | Statistical Analysis

Statistical analysis was performed using GENSTAT software (version 18). Combined analysis of variance (ANOVA) was conducted across each environment and zone. Duncan's Multiple range test was used to compare means whenever F-test was found significant. Environments were defined as combinations of seasons and agro-ecological locations.

3 | CHARACTERISTICS

3.1 | Grain yield performances

The combined ANOVA over 10 environments covering the four major agro-ecological of Morocco resulted in no significant differences between genotypes for average grain yield across environments (Table 3), but significant differences among genotypes could be found in certain environments (Table 4). High variance was noticed between environments for grain yield as result of the vast climatic variations, in particular the rainfall amount and the temperatures levels recorded at each location. Highly conductive environments for grain yield include mostly the favorable zones with abundant moisture, while the Atlas Mountain zones exhibited the lowest values for all the traits (Table 4).

The overall average grain yield across cultivars was 3.01 t ha^{-1}. While there were no significant differences overall, Nachit demonstrated superior performances in arid zones presenting the highest grain yield value (3. 32 t ha^{-1}) attesting of its good tolerance to drought. Nachit exhibits a narrow root angle suitable to finding residual moisture in the deeper soil layers (El Hassouni et al., 2018), and larger kernels that are a fundamental element of grain yield in durum wheat (Jabbour et al., 2022).

3.2 | Morpho-physiological characteristics

The plant height, number of days to heading, and number of days to maturity were recorded over seven, four, and four environments, respectively, and are presented in Table 3. Plant height ranged from 86 cm for 'Marwane' cultivar to 93 cm for Nachit (Table 3) This is an important finding since Moroccan farmers prefer taller cultivars capable of producing more straw for animal feeding, since straw often fetches equal or higher price than grains at the local market (Alary et al., 2020). The number of days to heading varied among genotypes from 89 to 95 days, while maturity was achieved between 147 and 149. Thus, Nachit is an early flowering type achieving heading in

TABLE 2 Agro-ecological Characteristics of experiment sites in Morocco.

Site	Coordinates	Agro-ecological zone	Annual moisture (mm)	Temperature (°C) Min.	Temperature (°C) Max.
Sidi Allal Tazi	34°31′ N 6°19′ W	Favorable humid	514	5	33
Marchouch	33°60′ N 6°7′ W	Favorable rainfed	375	7	32
Douyet	34°00′ N 5°00′ W	Favorable rainfed	410	5	31
Khemis Zemamra	32°37′ N 8°42′ W	Arid	250	12	28
Jemaa Shaim	32°40′ N 10°00′ W	Arid	256	8	35
Sidi El Aidi	33°9′ N 7°24′ W	Arid	237	3	35
Annoceur	33°41′ N 4°51′ W	Highland	500	−7	40

TABLE 3 Field performance of Nachit and seven other durum wheat cultivars in Morocco 2017–2019.

Cultivar	Grain yield (t/ha)	Protein content (g/kg)	1000 kernel weight (g)	Plant height (cm)	Days to heading[a]	Days to maturity[a]
Nachit	3.32a	149.8a	52.24a	93.51a	89c	147a
Marzak	3.35a	147.4ab	45.58b	90.88ab	91bc	148a
Marwane	2.36a	145.1ab	38.57de	86.01c	92ab	149a
Hamadi	3.24a	141.2cd	41.17c	91.72ab	95a	149a
Irden	2.94a	143.5bcd	40.47cd	91.13ab	93ab	149a
Amria	2.94a	141.0cd	41.43c	89.17abc	95a	148a
Chaoui	2.79a	140.7cd	38.01e	90.58abc	94ab	148a
Karim	3.17a	137.6d	44.58b	87.89bc	93ab	149a
Mean ± SE	3.01 ± 0.29	143.3 ± 1.92	42.76 ± 0.98	90.11 ± 1.53	93.10 ± 0.99	148 ± 0.49
$LSD_{.05}$	0.749	5.350	1.951	4.340	2.793	1.397
No. of environments	10	10	4	7	4	4

Note: Means with the same letter are not significantly different at $\alpha = 0.05$ according to the Duncan test.

[a]Days from germination

just 89 days, and an early maturing type in 147 days (Table 3). These are useful phenological distinction since early types are traditionally capable of completing their full cycle before the occurrence of terminal season stresses (Gupta et al., 2020).

3.3 | Reaction to disease

Natural occurrence of leaf rust (caused by *Puccinia triticina*) infection was recorded at five environments. Nachit confirmed good resistance to *Lr14 a* virulent pathotypes, which are prevalent in Morocco. In addition, Nachit was defined as resistant to *Warrior* type of yellow rust (caused by *Puccinia striiformis*) and *Ug99* stem rust (caused by *Puccinia graminis*) when tested at the rust screening platform of Izmir, Turkey and at the station of Debre Zeith, Ethiopia, respectively. Instead, screening of Nachit at the septoria disease (caused by *Septoria tritici*) platform in Bejja, Tunisia indicated a moderately susceptible response.

3.4 | Rheological quality characteristics

The combined ANOVA over environments and zones resulted in highly significant differences ($p < .001$) between genotypes for protein content (Tables 3 and 4). In particular, Nachit achieved significantly higher average of total protein content equal to 150 g kg^{-1} (15% dm; Table 3) raging from 120g kg^{-1} in highland zone to 165g kg^{-1} in favorable rainfed areas (Table 4). Furthermore, Nachit showed the highest performances in terms of 1000-kernel weight (52.24 g), exceeding the best check by 15%. Vitreousness, and whole-meal yellow index b* were measured for durum wheat cultivars in 10 environments (Table 5). Nachit exhibited the highest vitreousness (96.12%) and a good level of whole-meal yellow index b* (16.37)

4 | CONCLUSION

The cultivar Nachit is well adapted to low moisture conditions thanks to its earliness that favors avoidance of the

TABLE 4 Field performance of Nachit and seven other durum wheat cultivars in four agro-ecological zone in Morocco 2017–2019.

	Arid			Favorable rainfed			Favorable humid			Highland		
Zone/ genotype	**GY (t/ha)**	**PC (g/kg)**	**TKW (g)**	**GY (t/ha)**	**PC (g/kg)**	**TKW (g)**	**GY (t/ha)**	**PC (g/kg)**	**TKW (g)**	**GY (t/ha)**	**PC (g/kg)**	**TKW (g)**
Nachit	3.32a	148.1a	56.33a	4.19a	165.5ab	50.47a	2.28b	135.8a	56.50a	1.87a	120.0a	45.67a
Marzak	2.98bc	151.4a	49.67bc	4.23a	163.5abc	45.60bc	3.22a	133.0ab	43.27b	1.18cd	100.0b	43.78ab
Marwane	2.71cde	137.1a	43.03d	2.54c	168.9a	41.23cde	2.29b	125.0cde	35.00c	0.79d	114.0a	35.00c
Hamadi	3.04b	150.7a	49.40bc	4.12a	157.4c	40.73de	2.47b	121.8e	32.67c	1.87a	87.0c	41.85b
Irden	2.89bcd	145.1a	49.57bc	3.49b	163.2abc	41.90cd	2.52b	129.7bc	35.07c	1.69ab	86.3c	35.34c
Amria	2.63de	145.3a	49.80bc	4.02ab	157.8bc	41.37cde	1.96b	129.2bcd	40.77b	1.58abc	84.0c	33.78c
Chaoui	2.52e	147.7a	45.97cd	3.63ab	159.2bc	37.30e	2.05b	123.1e	34.13c	1.81ab	80.7c	34.64c
Karim	2.97bc	137.7a	53.23ab	4.22a	158.0bc	47.77ab	2.26b	124.0de	41.20b	1.36bc	82.0c	36.13c
Mean ± SE	2.88 ± 0.09	145.4 ± 4.41	49.62 ± 1.54	3.81 ± 0.20	161.7 ± 2.45	43.30 ± 1.36	2.38 ± 0.19	127.7 ± 1.80	39.83 ± 1.59	1.52 ± 0.13	94.4 ± 3.27	43.30 ± 2.98
$LSD_{.05}$	0.262	12.500	4.690	0.572	6.900	4.094	0.541	5.180	4.824	0.404	9.920	1.365

Note: Means with the same letter are not significantly different at α = 0.05 according to the Duncan test. GY, grain yield; PC: protein content; TKW: 1000-kernel weight.

TABLE 5 Other grain quality attributes of Nachit and others durum wheat cultivars.

Cultivar	Vitreousness (%)	Whole-meal yellow index b*
Nachit	96.12a	16.37b
Marzak	92.53ab	14.88cd
Karim	92.92ab	15.53c
Hamadi	93.29ab	17.45a
Irden	93.57ab	14.48d
Amria	90.17b	14.36d
Marwane	89.57b	14.95cd
Chaoui	90.31b	14.41d
Mean ± SE	92.31 ± 1.790	15.12 ± 0.212
$LSD_{.05}$	4.990	0.590
No. of environments	10	10

Note: Means with the same letter are not significantly different at α = 0.05 according to the Duncan test.

worst terminal stresses, its narrow root angle suitable to finding residual moisture in the deeper soil layers, and its larger kernels that are a fundamental element of grain yield in durum wheat. Considering its large grain size and earliness, Nachit has a very high grain filling rate that could be exploited also for breeding adaptation to other environments.

Therefore, the use of a crop wild relative in crop improvement has resulted in the successful release of Nachit, a cultivar ideally suitable for cultivation in the harsh dry conditions of Morocco. Besides grain yield performances, it outperformed all commercial checks in terms of high protein content and large grain size. In addition, Nachit possesses an ideal package of resistance to all three rusts combined with an ideal earliness and taller stance. The licensing process for Nachit cultivar is in progress through an open tender system for both the public and the private sectors, but Nachit is expected to be available to farmers for commercial cultivation by 2025.

5 | AVAILABILITY

The National Institute of Agricultural Research (INRA), PO Box 415, Rabat, Morocco, and The International Centre for Agricultural Research in the Dry Areas (ICARDA) Rabat are maintaining breeder seed of Nachit. Requests for seed may be sent to the Director of INRA, ICARDA or to the corresponding author of this publication. Seed of Nachit has also been deposited into USDA-ARS National Library for Genetic Resources, where it will be available five years after publication.

AUTHOR CONTRIBUTIONS

Mona Taghouti: Conceptualization; data curation; formal analysis; writing – original draft. **Filippo Maria Bassi**: Methodology; supervision. **Nsarelhaq Nasrellah**: Investigation. **Ahmed Amri**: Conceptualization. **Jihan Motawaj**: Investigation. **Miloudi Nachit**: Conceptualization; data curation; funding acquisition; investigation; methodology; resources; supervision; validation; visualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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