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Adaptation and Agronomic Performance of Domesticated Moroccan Oat (*Avena magna* ssp. *domestica*) Lines under Subsistence Farming Conditions at Multiple Locations in Morocco

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Abstract: Common hexaploid oat (*Avena sativa* L.) is an important global cereal crop. A Moroccan tetraploid sister species, *A. magna* Murphy et Terrel, was exclusively a wild species until recently. The goal of domestication was to exploit its superior groat-protein content and climatic tolerances. We set up replicated trials of 41 domesticated *A. magna* lines on eight Moroccan farms during the 2017–18 and 2018–19 growing seasons. Twenty traits were measured and analyses of variance detected significant differences among lines. The highest grain yield was at Berrechid in 2017–18 (63.56 q/ha), with an average annual yield across sites of 43.50 q/ha, the site factor explaining 82% and the genotype-environment interaction explaining 15% of the variability. In the second year, El Kebab recorded the highest yield at 20.03 q/ha over the annual average of 14.78 q/ha. In this second year, the site factor was highly significant, explaining 42.25% of the variation, with the genotype-environment interaction explaining 26.61% of the variability. An additional main effect and multiplicative interaction analysis of the eight two-year trials identified several accessions with good yield stability. Twelve lines exhibited a ASVs ≤ 1.50, with five accessions (A34, A40, A23, A05, A04) exceeding the overall average yield of 29.53 and A34 having the greatest mean grain yield and stability. The versatility and stability of *A. magna* can provide a sustainable protein source and an economic resource for farmers seeking products that are resilient to climatic instability.

Keywords: *Avena magna* ssp. *domestica*; oat; subsistence farming; seed protein; neodomestication

1. Introduction

The oat genus *Avena* L. ($x = 7$) includes the seventh most important cereal worldwide: common or white oat (*A. sativa* L. $2n = 6x = 42$; AACCDD subgenomes). Other domesticated taxa include red oat *A. byzantina* C. Koch (AACCDD), a fodder oat grown in mild winter-production conditions; Ethiopian endemic oat *A. abyssinica* Hochst (AABB); the diploid lopsided or sand oat complex (*A. strigosa* Schreb. A_sA_s); and the recently domesticated *A. magna* Murphy et Terrel ssp. *domestica* Ladizinsky [1]. The oat genus' center of origin is the Maghreb and southern Iberia, though the most likely tetraploid progenitor of the hexaploid species—*A. insularis* Ladizinsky (CCDD)—is currently found only in Tunisia and Sicily in the central Mediterranean [2,3]. The hexaploid cultivated forms appear to have been domesticated from weedy *A. sterilis* L. on at least two occasions in the ancient Near East [4,5], with a secondary center of diversification of the hulless or naked oat in Northwest China and Mongolia [6].

Avena magna (Moroccan oat) was recognized by Ladizinsky [1] as having approximately double the seed protein content of common oat. Consequently, Ladizinsky embarked upon a project to transfer some components of the domestication syndrome—reduced awn length, glabrous lemma and palea, non-shattering seed, and white hull color—from hexaploid common oat to tetraploid Moroccan oat through sexual hybridization using two cycles of backcrossing. One of his stable backcross lines displaying the domestication syndrome was Ba13-13. Oliver et al. [7] produced a linkage map for *A. magna* from a Ba13-13 × wild #169 recombinant inbred line (RIL) population containing 1013 molecular, three morphological, and one cytological marker arranged in 14 linkage groups. They also found that the domestication syndrome components displayed by Ba13-13 were associated with inheritance of genomic material from hexaploid oat and were distinguished from wild *A. magna* and similar-phenotype RILs by lack of a cytological knob on chromosome 5C. The tight linkage in the coupling phase with genes controlling shattering (*Ba*) and awn formation (*Awn*) at the terminus of linkage group 13 (chromosome 5C), with the third major gene for lemma pubescence (*Lp*) near the terminus of linkage group 11, suggested that these traits could be easy to retain in further crosses to develop a broad, diverse gene pool for cultivated Moroccan oat breeding. Unfortunately, while the domestication syndrome transfer from hexaploid oat into *A. magna* represented an improvement over wild *A. magna*, introduction of other traits important for broad cultivation, such as awn deletion, complete resistance to shattering, semi-dwarfism, lodging resistance, erect growth habit, resistance to seed dormancy, phototropism (reduced time to flower and maturity), reduced groat length, and ease of dehulling proved difficult while retaining high seed protein content [8,9].

Years of further work, beginning with a wild-phenotype F_3 plant from the Ba13-13 × #169 population as described by Jackson [9], resulted in a series of genetically diverse *A. magna* lines having improved domestication traits without relying on the hexaploid 5C chromosomal material while retaining a protein content exceeding 25%. Moreover, this new domesticated species should be well adapted to changing climatic conditions in its native Morocco, where models forecasting 2–3 °C temperature increases and 10–20% precipitation decreases by 2050 have prompted policy changes away from optimizing and towards stabilizing crop production [10]. Additionally, the increased macro- and micrnutrient density of Moroccan oat [9] could help address stunting and other malnutrition problems that persist in the country, especially in rural areas [11]. The present study was designed to assess genetic diversity, yield stability, and overall adaptive behavior of 41 *A. magna* domesticated lines through eight agro-morphological characterization trials at seven geographically and climatically diverse sites in Morocco spanning the 2017–18 and 2018–19 growing seasons.

2. Materials and Methods

2.1. Plant Materials

Avena magna ssp. *domestica* lines in this study were developed from a single Ba13-13 × wild #169 recombinant inbred line (RIL) [7] expressing the wild-type growth habit and resistance to field races of crown rust (*Puccinia coronata*) in Baton Rouge, LA [9]. Seed from this line was subjected to six cycles of selfing and selection for improvements in agronomic and seed domestication, resulting in six foundational lines displaying various combinations of traits for domestication and cultivation including awn reduction, shattering resistance, semi-dwarfism, lodging resistance, erect growth habit, resistance to seed dormancy, phototropism, reduced groat length, and ease of dehulling [9]. A set of 114 RILs, including the 41 experimental lines in this study (Table 1), were produced by intercrossing the foundational lines as instructed by a virtual pedigree produced using a genotype/phenotype model with the JMP Genomics software package (SAS Institute Cary, Cary, NC, USA). The 41 lines were compared to the internal control 'Avery' (A40), a commercial *A. magna* ssp. domestica variety produced by General Mills in 2013 [9] and released commercially in Morocco late 2019.

Table 1. List of accessions of *A. magna* ssp. *domestica* in this study.

N°	Accession	Pedigree	N°	Accession	Pedigree
1	A01	BAM_6/34_9	22	A26	BAM_34/55_22
2	A02	BAM_55/231_28	23	A27	BAM_55/231_22
3	A03	BAM_34/231_44	24	A28	BAM_55/231_35
4	A04	BAM_34/55_19	25	A29	BAM_55/231_40
5	A05	BAM_6/231_29	26	A30	BAM_6/235_16
6	A06	BAM_34/55_11	27	A31	BAM_34/55_5
7	A07	BAM_55/231_51	28	A32	BAM86/235/43
8	A08	M3_18X	29	A33	BAM_55/231_32
9	A10	BAM_6/235_20	30	A34	BAM_34/231_45
10	A11	BAM_34/55_6	31	A35	BAM_55/231_33
11	A12	96.5.34	32	A36	BAM_55/231_37
12	A13	BAM_6/34_28	33	A37	BAM_55/231_31
13	A14	BAM_6/235_44	34	A38	BAM_34/231_29
14	A15	BAM_34/231_20	35	A39	BAM_6/34_15
15	A16	100.2.235	36	A40	Avery (96.5.6)
16	A17	BAM_34/231_14	37	A41	BAM_34/235_21
17	A18	BAM_34/55_1	38	A42	M3_93X
18	A20	BAM_55/231_6	39	A43	BAM_55/231_41
19	A22	96.5.55	40	A44	BAM_55/231_38
20	A23	BAM_34/231_12	41	A45	BAM_34/55_36
21	A25	BAM_34/235_3			

2.2. Experimental Sites

Experimental site locations are mapped in Figure 1, shown photographically in Figure 2, and described in Table 2. Experimental trials of 2017–18 were conducted at four locations: a commercial potato production farm 14 km southeast of Berrechid (central Atlantic coastal plain); a modern production farm 15 km south of Meknes; a subsistence farm in Lahri (low-altitude, Khenifra region); and a subsistence farm 4 km southwest of El Kebab (high-altitude, Khenifra region). Trials were sown at Berrechid on 6 December 2017; at Lahri and El Kebab on 8 December; and at Meknes on 27 December. Experimental trials of 2018–19 were conducted in the fall–winter–spring growing season on an organic production farm 16 km west of Tiflet (northern Atlantic coastal plain); at the Royal Agricultural Domain Ain Hamra Farm in Seba Ayoun 20 km east of Meknes (north-central interior lowlands); at the El Kebab farm; and at a cooperative subsistence farm 18 km east of Youssoufia in Bouchane (semiarid Phosphate Plateau) with sowing dates of November 27, 28, 29, and 30, respectively. Locations were purposely selected to test the adaptational range of *A. magna* as a grain crop and, consequently, included a range of technological sophistication from commercial to subsistence; climate zones ranging from warm to cool and dry to humid; and traditional cultural contexts including both Amazigh (Lahri, El Kebab) and Arab (i.e., Bouchane).

Figure 1. Map showing locations of field trials of domesticated *A. magna* lines in Morocco in 2017-18 (**red**), 2018-19 (**blue**), and in both growing seasons (**purple**).

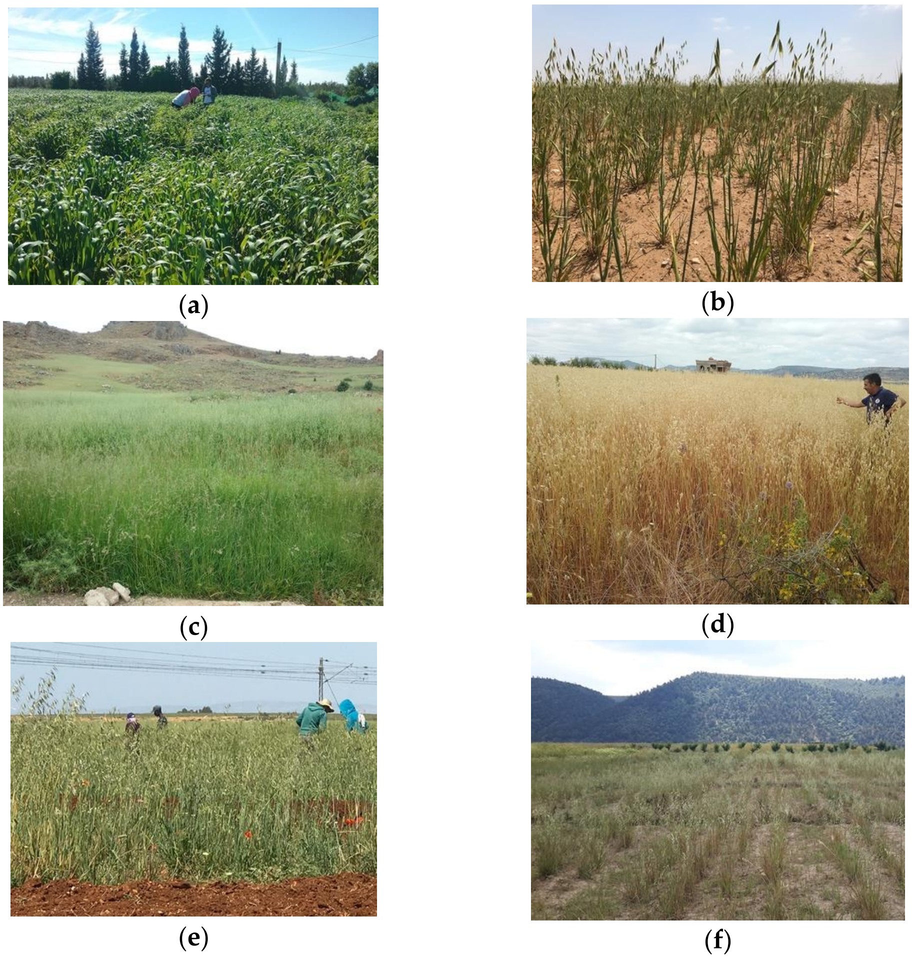

Figure 2. Experimental site photographs: (**a**) Berrechid, February 2018; (**b**) Bouchane, April 2019; (**c**) El Kebab, April 2018; (**d**) Lahri, May 2018; (**e**) Meknes, April 2019; (**f**) Tiflet, April 2019.

Table 2. Summary of climatic and soil conditions at the seven experimental sites. Actual rainfall and temperatures were based on data from nearby cities at worldweatheronline.com. El Kebab data was based on observations at Ain Leuh, 60 km northeast at a similar elevation and orographic orientation in the Middle Atlas Mountains; Meknes data was based on observations at Fes, 34 km northeast of the Seba Ayoun research site at similar elevation and environment. Lahri data were based on observations at M'rirt, 36 km north and at a similar altitude and orographic exposure.

Locations	Zone	Position			Soil Type	Temperature (°C)		Rainfall (mm)
		Latitude	Longitude	Altitude		Min	Max	
Berrechid 17-18	Central Coastal Plain	33.17713	−7.46983	220	Vertisols	6	43	203.7
Bouchane 18-19	Phosphate Plateau	32.2433	−8.3294	330	Cambisols	10	44	201.5
El Kebab 18-19	Middle Atlas Mountains	32.7071	−5.5326	1540	Fluvisols	2	36	300.2-390.3
Lahri 17-18	Middle Atlas Foothills	32.8427	−5.6108	847	Regosols	−4	45	283.9
Meknes 17-18	Saïss Plain	33.8519	−5.6608	600	Regosols	−0.3	43.0	205.2
Meknes 18-19	Saïss Plain	33.9067	−5.3170	546	Cambisols	0	43	612.8
Tifelt 18-19	North Coastal Plain	33.8747	−6.5077	115	Fluvisols	6	36	266.8

Soil and climatic data at each of the seven experimental locations are provided in Table 2. The Bouchane and Tiflet experiments were placed on sites that had unworked fallow fields during the previous year. Tillage was performed using two moldboard cross-passages for the Berrechid, Bouchane and Meknes sites and using conventional tillage at the Tiflet and El Kebab sites. The sowing dose was determined for each line as a function of the germination rate of the seed. Weed control was done by hand, which took place over two periods: at the tillering and flowering stages. The number of weedings was based on the degree of weed infestation. For example, the Tiflet site was repeatedly weeded in accordance with the organic management of the farm. However, the Bouchane site experienced minimal weed infestation due to the exceptionally dry conditions. At El Kebab, nitrogen fertilization was carried out at the early tillering stage in the form of ammonium nitrate. Weather data from nearby stations and presented in Table 2 reveal that December was very dry in both years, but especially following planting in 2018-19, and that sufficient rainfall to support abundant crop growth did not occur until very late in the growing season in March-April. Additionally, it should be noted that average temperatures were low throughout the winter of 2017-18 in the Middle Atlas region encompassing the El Kebab site.

2.3. Experimental Design

The experimental set-up at the 2017-18 locations was in randomized complete blocks (RCB) with two repetitions. Planting was done in paired three-meter rows, spaced 20 cm apart, with a seeding rate of 5 g per paired lines. The spacing between lines was 60 cm. Each site was characterized by peculiarities or variations in the planting plan in accordance with terrain constraints. The experiments in 2018-19 were set up in randomized complete blocks (RCB) with 1.83 m rows in three blocks at Meknes and Tiflet; 1 m rows with three blocks at El Kebab; and 2 m rows with three blocks at Bouchane.

2.4. Measurements and Observations

Agronomic and morpho-physiological characteristics were measured to estimate yield potential through grain and straw productivity; yield stability across environments; tolerance to the three main oat diseases (crown rust (CR), barley yellow dwarf virus (BYDV), powdery mildew); and to determine the most optimally and stably productive lines in terms of yield. Measurements were taken at three different growth stages in order to carry out the disease and agro-morphological measurements.

At the flowering stage, rust resistance was assessed using a scale based on the percentage of leaf cover by the pathogen (severity of the disease). Tolerance to both powdery mildew and BYDV were assessed based on "presence" or "absence", though powdery mildew was only scored in 2017-18. The evaluation of the three diseases was made for each line at the four sites in 2017-18, though powdery mildew presence was erratic and was therefore omitted from the final analyses.

Observations were made on a sample of four plants at the seedling stage and on three samples from each plot at harvest. In each plot, we counted the stand and measured the agro-morphological parameters (stem height, length of the roots and number of tillers). For the individual plants, we separated the different organs (seeds, stems, roots) apart to determine their dry weight. For the rest of the plots, we also separated the seeds from the remaining biomass. All of the harvested tissue was then weighed after oven-drying at 70 °C for 48 h for stems, roots, and biomass and at 35 °C for 48 h for seeds hulled after threshing. From these measurements the harvest index was then calculated using Equation (1), after estimating the grain yield and straw yield.

$$HI = \frac{GYH}{GYH + DYH} \tag{1}$$

where:

- *HI*: harvest index
- *GYH*: grain yield (q/ha)
- *DYH*: dry matter yield (q/ha).

For the estimation of grain and straw yields, we extrapolated the value of the average grain and straw yield of three random samples of 0.5 m row length. The thousand-seed weight was calculated by counting and weighing the threshed and oven-dried seeds. This allowed us to calculate the number of grains per individual plant using the following formula:

$$N_{grains} = \frac{P_{grains} \times 1000}{TSW} \tag{2}$$

where:

- N_{grains}: number of seeds per plant
- P_{grains}: grain weight per plant
- *TSW*: thousand-seed weight

At maturity, a sample of three individuals per line, block and site; and a sample from three 0.5 m row length per line, block and site constituted the material on which we carried out measurements and estimated the agro-morphological variables.

2.5. Statistical Analyses

The collected data were used to carry out statistical analyses. We assessed intra-locality variability by comparing the lines with each other at each agro-climatic site. On the one hand, the measured parameters were the subject of a descriptive analysis and an analysis of variance (ANOVA) with two sources of variation (lines and blocks). Before any analysis, the normality of the variables was tested for each indicator through a Kolmogorov–Smirnov (KS) test at a significance level of 5%. If the null hypothesis was rejected, a test to compare the Student-Newman-Keuls means (SNK) was used to distinguish the different homogeneous groups. For experimental sites where the variables associated with productivity (grain yield, dry matter yield, harvest index) presented significant differences due to the effect of the genotype, we carried out a principal component analysis (PCA).

Lastly, interlocality and growing season analyses for data were performed using an ANOVA with three factors (lines, environments and blocks), a principal component analysis (PCA), and an ascending hierarchical classification (AHC). Then, the evaluation of the genotype × environment (G×E) interaction on the basis of all the parameters evaluated was carried out using an additive main effects and multiplicative interaction (AMMI) analysis. The AMMI is a hybrid procedure that provides visual inspection and interpretation of the components of the yield G×E interaction [12]. The AMMI model separates the main additive effects from genotypes and environments using ANOVA, and then analyzes the effect of interaction using the multiplicative model provided by the PCA. This analysis mainly provides information on the productivity and stability of the genotypes. Consequently, the AMMI stability value (ASV) was used to quantify genotype yield stability as a function of the first two axes of the main components of the interaction, and was calculated according to the formula developed by Purchase [13–15]:

$$ASV = \sqrt{\left[\frac{SSA1}{SSA2}(IPCA1)\right]^2 + (IPCA2)^2} \quad (3)$$

where:

- *SSA1*: sum of squares of the interaction component of the first axis of the PCA
- *SSA2*: sum of squares of the interaction component of the second axis of the PCA
- *IPCA1*: ACP score of the interaction first axis component
- *IPCA2*: score of the interaction second axis component.

IBM SPSS Statistics for Windows (IBM Corp., Armonk, NY, USA) was used for obtaining descriptive statistics, analyses of variance, and principal component analysis. Stat-Box (Spriteworks Developments) is statistical analysis and data processing software that was used to display PCA plots. Minitab 17 (Minitab, State College, PA, USA) was used for descriptive analyses and hierarchical classifications. For AMMI we used open-source R versions 3.5.0 and 3.6.1 software [16].

3. Results and Discussion

3.1. Intra-Locality Analyses

3.1.1. Assessments of Disease Tolerances

The observation of diseases was carried out in the middle of the cycle for all crops, specifically on the 92nd, 111th, 118th, and 156th days after sowing at the Meknes, Berrechid, Lahri, and El Kebab sites in 2017-18, respectively. The three most important diseases attacking oats in Morocco are crown rust (Puccinia coronata f. sp. avenae), BYDV, and powdery mildew (*Blumeria graminis* f. sp. *avenae*). Crown rust developed by the middle of the cycle at the Berrechid site but was not observed at the other locations until very late in the growth cycle. We therefore assessed crown rust severity only at Berrechid via visual scoring using the modified Cobb scale [17]. Following this we performed a two-factor ANOVA, with the summary table showing only significant differences presented in Table 3. Powdery mildew was only observed at Berrechid and was therefore not scored. As for BYDV, it was observed at all sites, though infestations within a given site did not appear to be uniform.

In the 2018–19 experiments, observations of diseases were made on the 152nd day after sowing at the Meknes and El Kebab sites and on the 154th and 161st days for the Bouchane and Tiflet sites, respectively. The assessment focused on two diseases: crown rust and BYDV.

For the assessment of crown rust tolerance, the lines and blocks terms showed no significant differences among the 41 lines (Table 3) in 2017-18. On the other hand, the lines*blocks interaction showed a highly significant difference, indicating that there was likely a non-uniform infestation across the plots—something that should not be surprising given that oat is a rare crop in these growing areas of central Morocco. During a 209th day post-sowing visit at Lahri, controls T1 and T2, as well as lines A01, and A02 displayed crown rust symptoms. At Meknes and El Kebab, we noticed some symptoms of crown rust on several lines at harvest time.

Table 3. Summary two-factor ANOVA table for significant disease traits. Crown rust (*Puccinia coronata* f. sp. *avenae*) infestation was sufficiently uniform to allow for assessment at Berrechid in 2017-18 and at all sites in 2018-19. NS = not significant; *significant at $p = 0.05$; **significant at $p = 0.01$; ***significant at $p = 0.001$.

Site and Season	Trait	Genotype	Block	Genotype × Block
Berrechid 17-18	CR	-	-	-
	BYDV	NS	NS	NS
Bouchane 18-19	CR	2.220 ***	1.824 NS	1.133 NS
	BYDV	2.904 ***	2.445 NS	2.479 ***
Lakbab 18-19	CR	NS	NS	NS
	BYDV	3.602 ***	6.446 **	1.681 **
Meknes 18-19	CR	-	-	-
	BYDV	10.389 ***	79.822 ***	14.032 ***
Tiflet 18-19	CR	2.303 **	-	-
	BYDV	4.712 ***	4.478 *	5.251 ***

As expected, the appearance of crown rust depended heavily on the climatic conditions of the test site. Whereas crown rust only partly appeared in 2017-18 at Berrechid, the disease only appeared at Bouchane and Tiflet in 2018-19. According to the ANOVA results from the Bouchane site (Table 3), significant differences were found among lines, while the non-significant differences for crown rust infestation detected by the line*block ANOVA interaction indicated there was uniform infestation throughout the plots. At Tiflet, the infestation was assessed on only the first block; however, from the ANOVA it is clear that there were significant differences among the lines and there was likely an exogenous source of the inoculum. Because of its relative proximity to the Atlantic Ocean, the Tiflet site experiences chronic crown rust infestations [18]. The narrow gradient of the distribution can be explained by the dissemination of the pathogenic agent into the experimental plot, which was cleared of riparian vegetation and cultivated for the first time for this particular study.

Since humid conditions favor the development of the Puccinia coronata fungus, drought conditions during winter 2018–19 at Meknes and El Kebab likely explained the absence of crown rust infestations at these study sites. This can also possibly be explained by local applications of fungicides on nearby cereal fields, especially at Meknes where the plots were located on a large commercial farm within the Domaine Royaume. This hypothesis is supported by the results from the prior year's study when little crown rust appeared, in spite of more abundant precipitation.

The means comparison for degree of BYDV infestation at El Kebab in 2018-19 enabled us to distinguish three homogeneous groups, with lines A01 and A03 being the most susceptible (data not shown). The average infestation at El Kebab was the lowest in both growing seasons.

For BYDV, the disease was present at all sites, with by far the highest incidence being at Tiflet. This observation is not surprising, given the relative abundance and diversity of aphid vectors of this disease [18,19], combined with *A. magna*'s well-known susceptibility to BYDV [1]. However, the lowest incidence of BYDV in both growing seasons was at El Kebab, suggesting that the relatively lower temperatures, higher elevation, and distance from oceanic humidity at this site were unfavorable for the aphid vectors of this disease. Future *A. magna* germplasm enhancement will have to put more effort into BYDV tolerance, but it will likely rely on variation induction because of the lack of resistance genes in the wild species [1].

3.1.2. Analyses of Agro-Morphological Traits

Significant agro-morphological effects at the eight environments are highlighted via descriptive statistics provided in Table 4 and two-way ANOVA Table 5. Variables studied included the measured parameters, the calculated parameters, the thousand-seed weight (TSW) and the harvest index (HI).

Agro-morphological evaluation of the *A. magna* lines was performed for the following characters: plant height (PH), root length (RL), number of fertile tillers per plant (NFT), root weight (RW), dry matter weight per plant (DYP), grain yield per plant (GYP), number of grains per plant (NGP), thousand-seed weight (TSW), grain yield per hectare (GYH), dry matter yield per hectare (DYH), and harvest index (HI).

Descriptive statistics of the agro-morphological traits are presented in Table 4. Based on the internal analyses at each site, PH and TSW were the most stable variables as they present low coefficients of variation. The highest CVs were observed for DYP, NGP, and GYP. In the first growing season of 2017-2018, plant development was much greater than the second season. The PH values measured between 110.24 and 176.86 cm in the first year and 45.15 and 79.14 cm the second year, and the average grain yield between 36.79 and 14.78 q/ha in the two years, respectively.

Table 4. Descriptive statistics for the agro-morphological traits at the eight locations.

Site	Berrechid 17-18		Meknes 17-18		Lahri 17-18		ElKebab 17-18		Bouchane 18-19		ElKebab 18-19		Meknes 18-19		Tiflet 18-19	
Traits	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
PH	144.78	8.91	176.86	8.53	162.18	7.81	110.24	12.84	45.15	19.93	66.88	19.33	79.14	20.64	56.20	23.05
RL	18.16	20.43	16.70	19.77	15.83	29.52	10.96	30.68	16.70	23.2	16.9	19.37	15.32	22.17	7.84	26.44
NFT	5.53	39.45	5.45	48.93	5.98	57.99	7.66	43.33	3.06	44.20	3.59	56.63	3.83	32.17	2.51	45.97
RW	3.72	64.34	7.42	61.62	7.08	109.98	4.28	153.54	1.43	79.98	1.89	71.12	4.38	68.27	2.01	57.87
DYP	28.01	51.58	32.86	55.46	33.22	56.72	14.96	85.33	9.67	82.39	16.99	66.97	37.96	54.55	8.07	55.69
NGP	238.35	51.84	267.22	63.36	129.56	79.23	152.98	76.48	197.95	84.90	184.28	72.65	246.37	94.95	110.81	43.35
GWP	8.62	53.04	10.34	63.33	26.15	82.21	6.32	75.79	6.41	85.46	8.57	71.67	8.33	92.04	2.24	67.46
TSW	36.13	6.78	38.98	11.09	41.01	12.12	41.48	10.00	32.35	10.55	46.87	10.36	34.11	8.96	18.96	21.67
GYH	63.72	40.42	56.56	44.03	29.95	62.54	23.94	45.22	14.90	88.71	20.03	77.37	19.11	96.54	5.09	72.05
DYH	255.55	35.49	195.54	42.08	140.78	37.82	6.29	46.55	22.53	86.41	39.67	69.74	79.14	62.27	18.07	62.40
HI	20.15	25.58	22.57	16.14	17.99	47.63	30.08	21.22	39.24	23.48	33.39	31.83	18.72	66.32	23.70	59.06

Explanations: PH = plant height (cm); RL = root length (cm); NFT = fertile tiller number; RW = root weight (g); DYP = dry matter weight per plant (g); NGP = number of grain per plant; GWP = grain yield per plant (g); TSW = thousand-seed weight (g); GYH = grain yield per hectare (q); DYH = dry matter yield per hectare (q), HI = harvest index.

In the 2018–2019 season, Bouchane had the shortest plant size (45.15 cm) in comparison to the other sites, and the average RL of the lines was more proportionate to the PL than at the other sites. This demonstrated the capacity of *A. magna* ssp. domestica roots to penetrate deeply into sandy-loamy soils under harsh growing conditions (Figure 2).

The accessions in Tiflet presented the lowest values for the agro-morphological parameters (Table 4). We suspect this was mainly due to the poorer growing conditions of the trial of the new managed loamy-sandy soil of an organic farm. The plants were also exposed to severe competition from weeds, pests, and diseases, which strongly impacted the growth and development of the lines (Figure 2).

The two-factor ANOVA revealed significant differences among accessions. At Berrechid, the genotype effect was highly significant for the variables PH and GYH and moderately significant for RW and HI (Table 5). The line*block interaction was moderate for the PH parameter and minor for RW, NGP, GYP, and GYH.

The Bouchane site ANOVA analysis showed highly significant genotypic effects for six of ten variables (NFT, RW, GYP, GYH, DYH, and HI), a moderate effect of PH, and a minor effect of RL (Table 5). The block factor had significant effects on all the variables except RL. The line*block interaction effect was highly significant for PH, moderate for RW and GYP, and significant at the 5% level for the rest of the parameters.

Table 5. Summary of the two-factor ANOVA per environment for significant agro-morphological and productivity trait differences.

SITE	TRAIT	G	B	G×E	SITE	G	B	G×E
Berrechid 17-18	PH	2.322 ***	0.002	2.120 **	**Bouchane 18–19**	1.911 **	31.907 ***	1.979 ***
	RL	1.167	1.898	0.906		1.636 *	1.697	1.327 *
	NFT	1.653 *	0.508	1.372		5.154 ***	10.994 ***	1.21 *
	RW	1.927 **	0.149	1.517 *		2.213 ***	11.474 ***	1.545 **
	DYP	1.379	1.064	0.942		1.143	9.096 ***	1.412 *
	NGP	1.345	0.185	1.619 *		1.115	15.769 ***	1.1.454 *
	GYP	1.555 *	0.123	1.580 *		1.346 ***	15.645 ***	1.509 **
	GYH	2.597 ***	0.102	1.608 *		2.443 ***	13.193 ***	1.45 *
	DYH	1.473 *	2.363	1.084		2.298 ***	7.794 ***	1.33 *
	HI	1.972 **	1.156	0.974		2.730 ***	16.038 ***	1.367 *
Meknes 17-18	PH	3.290 ***	0.524	1.503	**El Kebab 18–19**	4.205 ***	75.125 ***	1.275
	RL	1.729 **	4.028 *	1.719*		2.258 ***	0.186	1.11
	NFT	1.408	1.756	0.272		8.919 ***	0.102	1.567 **
	RW	1.565 *	0.665	0.837		5.906 ***	1.153	1.533 **
	DYP	1.736 **	0.508	0.744		3.360 ***	4.135 **	1.659 **
	NGP	1.517 *	1.226	1.121		2.565 ***	3.687 *	2.223 ***
	GYP	1.503 *	1.118	1.073		3.517 ***	3.894 *	1.533 **
	GYH	1.095	1.806	1.388		5.936 ***	2.563	1.66 **
	DYH	1.495 *	1.407	1.942		4.818 ***	2.669 *	1.814 ***
	HI	2.596 ***	0.104	2.668 ***		2.565 ***	3.687 *	2.223 ***
Lahri 17-18	PH	3.789 ***	8.825 ***	3.004 ***	**Meknes 18–19**	5.310 ***	97.559 ***	4.521 ***
	RL	4.147 ***	45.604 ***	4.414 ***		3.177 ***	1.663- *	0.950
	NFT	2.665 ***	17.458 ***	2.971 ***		2.178 ***	0.699	1.779 ***
	RW	1.460	14.674 ***	1.557 *		3.736 ***	14.137 ***	1.520 **
	DYP	2.655 ***	17.967 ***	2.646 ***		4.547 ***	12. 486 ***	1.954 ***
	NGP	1.754 **	8.224 **	2.565 ***		2.213 ***	14.162 ***	2.809 ***
	GYP	3.575 ***	11.455 **	3.343 ***		1.826 **	14.535 ***	2.808 ***
	GYH	2.522 ***	7.436 **	2.306 ***		1.989 **	14.264 ***	2.890 ***
	DYH	2.333 ***	10.240 **	1.698 *		8.051 ***	11.625 ***	2.127 ***
	HI	3.965 ***	21.860 ***	2.928 ***		3.564 ***	60.713 ***	3.448 ***
Lakbab 17-18	PH	2.442 ***	0.54	2.447 ***	**Tifelt 18–19**	2.741 ***	1.097	2.821 ***
	RL	1.636 *	1.697	1.327 *		2.449 ***	1.961	1.814 ***
	NFT	5.154 ***	10.994 ***	1.210		1.121	2.058	1.877 ***
	RW	2.213 ***	11.474 ***	1.545 **		3.677 ***	2.938	1.091
	DYP	1.143	9.096 ***	1.412 *		3.917 ***	4.218 *	2.206 ***
	NGP	1.089	1.091	1.305		294.401 ***	0.010	0.019
	GYP	1.173	0.917	1.343		614.688 ***	0.008	0.016
	GYH	2.443 ***	13.193 ***	1.45 *		814.991 ***	0.097	0.99
	DYH	2.289 ***	7.794 ***	1.330 *		5.566 ***	3.400 *	1.728 ***
	HI	2.728 ***	16.010 ***	1.367 *		20.186 ***	4.126 *	2.203 ***

Explanations: G = genotype; B = environment (Block); G×E = genotype by environment interaction; PH = plant height (cm); RL = root length (cm); NFT = number of fertile tillers; RW = root weight (g); DYP = dry matter yield per plant (g); NGP = number of grains per plant; GYP = grain yield per plant (g); GYH = grain yield per hectare (q); DYH = dry matter yield per hectare (q); HI = harvest index. *Significant at $p = 0.05$; **significant at $p = 0.01$; ***significant at $p = 0.001$.

At the Lahri site, the ANOVA (Table 5) showed no significant effects linked to the line factor for only RW. The block factor showed highly to moderately significant effects for all the traits. The line*block interaction showed highly significant effects for all parameters and slightly significant (at the 5% level) for RW and DYH.

At El Kebab the effect of the lines factor was highly significant for all the parameters in the 2018–2019 growing season but not significant for DYP, NGP, and GYP for the 2017–2018 season (Table 5). There was no significant block effect for PH, RL, NGP, and GYP for the first year trials. Finally, the line*block interaction was highly significant for PH in the first season and for NGP, DYH, and HI in the second season.

At Meknes, the 2018–2019 trial revealed significant differences among lines for GYP and GYH, and highly significant differences for the rest of the traits (Table 5). The block and line*block interaction factor effects were highly significant for PH, DYP, NGP, GYP, GYH, DYH, and HI, but the block factor was not significant for the NFT and the line*block interaction for RL.

At the Tiflet site, the test detected highly significant differences among the lines for all the variables except NFT (Table 5). The block factor had only a slightly significant effect on DYP, DYH, and HI and no effect on all other variables. The line*block interaction was highly significant for PH, RL, NFT, DYP, DYH, and HI but not for RW, NGP, GYP, and GYH.

3.1.3. Analyses of Productivity Traits

To assess the productivity of the *A. magna* oat lines, we analyzed the GYH, DYH, and HI of the eight experimental trials. Descriptive statistics for these productivity traits appear in Table 6 and the rankings of the 41 lines in Table 7.

In comparing the two seasons, genotype variability as measured by intra-site CV's was much higher in the second year (2018–19), 83.66% against 48.19% for GYH 70.21% against 40.47% for DYH, and 45.17% against 27.62% for HI (Table 6). For GYH, the greatest variability was found at Meknes (96.55%), which explains the high variability of HI in the same trial (0.66%). DYH was most variable at Bouchane (CV = 88.71%). Berrechid had the least variability for both productivity traits; GYH (40.69%), and DYH (33.98%). The highest HI variability (66.32%) was that of Meknes in the second trial season, 2018–2019.

In general, the productivity parameters for the 2017–18 trials were higher than the 2018–2019 trials, with respective means of 43.48 and 14.68 q/ha for GYH and 161.92 and 39.85 q/ha for DYH (Table 6). The HI values were lower in the first season with an average of 22.52% compared to the second season (28.76%). The overall mean grain yield was 29.08 q/ha, with the highest value at Berrechid (63.56 q/ha) followed by Meknes's first season (56.56 q/ha), and the lowest at Tifelt (5.10 q/ha). For DYH, the average overall yield was 100.89 q/ha with a maximum at Berrechid (255.08 q/ha) and a minimum at Tifelt (18.08 q/ha). The best HI was that of Bouchane (39.24%) and the lowest at Lahri (17.30%).

Table 6. Descriptive statistics for the productivity traits at the eight sites.

Site	Grain Yield (q/ha)		Dry Matter Yield (q/ha))		Harvest Index (%)	
	Mean	CV (%)	Mean	CV (%)	Mean	CV
Berrechid 17–18	63.56	40.69	255.08	35.42	20.12	25.49
Meknes 17–18	56.57	44.30	195.54	42.08	22.57	16.14
Lahri 17–18	29.95	62.54	140.78	37.82	17.30	47.63
El Kebab 17–18	23.94	45.22	56.29	46.55	30.08	21.22
First-year mean	43.50	48.19	161.92	40.47	22.52	27.62
Bouchane 18–19	14.90	88.71	22.53	86.41	39.24	23.48
El Kebab 18–19	19.74	77.37	39.68	69.74	33.40	31.83
Meknes 18–19	18.98	96.54	79.14	62.27	18.72	66.32
Tiflet 18–19	5.09	72.05	18.08	62.40	23.70	59.06
Second-year mean	14.78	83.66	39.85	70.21	28.76	45.17
Overall mean	29.14	65.93	100.89	55.34	25.64	36.40

In 2017–18, the Meknes site had the second-highest HI, with an average of 22.57%. The two lowest sites for HI in 2017–18 were Berrechid and Lahri, 20.12 and 17.30%, respectively. In the second-year trial, Bouchane, followed by El Kebab, presented the highest HI (39.24 and 33.40%, respectively), compared to Meknes and Tifelt at 18.72 and 23.70%, respectively (Table 6).

The two-way ANOVA detected highly significant differences for GYH among the 41 lines at all sites except Meknes in 2017–18 (Table 5). For DYH and HI, the differences were highly significant at six and eight sites, respectively, and were slightly significant (at the 5% level) at the Berrechid and Meknes first-year trials for DYH.

The overall ranking of lines for GYH, DYH, and HI are presented in Table 7. GYH ranged from a low of 16.96 q/ha for A22 to a high of 30.28 q/ha for A23; the A40 control line yield across the eight sites was 20.82 q/ha. DYH ranged from 64.44 to 102.83 q/ha with the respective accessions A22 and A02. For HI, A15 had the best value of 32.19% and A25 the lowest of 23.21%; the HI of the control, A40 was 24.36%.

Table 7. Ranking of top 41 lines for GYH, DYH and HI (Control = A40 "Avery").

N°	GYH		DYH		HI		N°	GYH		DYH		HI	
	Line	q/ha	Line	q/ha	Line	%		Line	q/ha	Line	q/ha	Line	%
1	A23	30.28	A02	102.83	A15	32.189	22	A45	24.29	A34	80.32	A31	26.096
2	A02	29.74	A23	98.22	A43	31.126	23	A11	24.17	A35	77.93	A05	26.093
3	A33	28.22	A41	94.85	A20	30.316	24	A26	23.99	A20	77.69	A03	26.013
4	A41	27.88	A16	94.54	A13	29.462	25	A27	23.92	A27	77.21	A11	25.972
5	A29	27.36	A32	91.94	A38	29.265	26	A30	23.88	A39	76.81	A02	25.686
6	A31	27.31	A17	90.31	A45	29.155	27	A17	23.44	A08	76.16	A10	25.593
7	A32	26.50	A01	88.50	A29	29.062	28	A38	23.41	A13	75.09	A12	25.569
8	A44	26.46	A25	88.09	A37	28.952	29	A06	23.24	A10	75.01	A41	25.317
9	A34	26.32	A29	87.53	A40	28.883	30	A01	23.20	A37	73.78	A27	25.187
10	A35	26.12	A30	87.09	A04	28.710	31	A36	23.00	A18	73.58	A14	25.128
11	A39	26.04	A06	86.27	A33	28.579	32	A08	22.78	A15	72.28	A42	24.825
12	A13	25.88	A31	86.22	A22	28.392	33	A07	22.61	A42	72.17	A06	24.799
13	A16	25.81	A33	85.74	A36	28.214	34	A14	22.37	A12	70.95	A07	24.720
14	A04	25.78	A03	84.32	A32	28.099	35	A25	21.95	A38	70.81	A17	24.450
15	A05	25.69	A04	83.98	A18	28.034	36	A10	21.27	A43	70.43	A30	24.390
16	A20	25.63	A05	83.68	A34	27.566	37	A40	20.82	A45	69.37	A01	24.358
17	A37	25.54	A44	81.69	A35	27.071	38	A28	20.32	A40	69.12	A08	24.346
18	A43	25.33	A07	81.62	A23	27.024	39	A42	19.93	A36	66.67	A39	23.766
19	A15	25.17	A11	81.56	A44	26.948	40	A12	19.91	A28	66.27	A16	23.408
20	A18	24.38	A26	80.74	A28	26.787	41	A22	16.96	A22	64.44	A25	23.214
21	A03	24.33	A14	80.35	A26	26.374							

In the first year of trials, A35, A27, and A14 ranked first in Berrechid for GYH, reaching yields of 108.73, 88.85, and 85.45 q/ha, respectively (Table 8). The control (A40) yielded 73.18 q/ha while line A22 produced the lowest GYH (38.83 q/ha) at the site. Meknes the second-best site; A37 and A16 ranked first with GYH at 83.90 and 75.02 q/ha, respectively; line A40 produced 61.82 q/ha; and the last lines, A36 and A13, yielded 39.22 and 34.87 q/ha, respectively.

In the first-year trials at El Kebab, lines A04, A15, and A25 had the lowest GYH 15.09, 15.23, and 15.41 q/ha, respectively, the control yield was 20.08 q/ha, and A36 and A38 recorded the highest GYH, 44.80 and 38.34 q/ha, respectively. The most productive line in Lahri, A16, produced 48.57 q/ha and the lowest yielding accession, A42 produced only 9 q/ha.

In the second-year trial in Bouchane, lines A10, A12, A22, and A42 ranked last for GYH, 9.08, 8.44, 7.96, and 7.94 q/ha respectively (Table 8). A40, the control, produced 9.14 q/ha, and line A20 presented the highest GYH, 28.86 q/ha. At El Kebab, lines A12, A15, and A22 had the lowest GYH, 6.39, 5.29, and 2.34q/ha, respectively, and A02 and A41 recorded the highest yields, respectively 44.80 and 38.34 q/ha as compared to the control yield of 14.33 q/ha at the same site.

Table 8. Ranking of the 41 lines for GYH at the eight locations. Berrechid was the highest yielding location in 2017–18, and El Kebab, the highest yielding location in 2018–19. Yields are provided in q/ha. Line A40 is the control accession.

Rank	Berrechid 17-18		El Kebab 17-18		Lahri 17-18		Meknes 17-18		Bouchane 17-18		El Kebab 18-19		Meknes 18-19		Tiflet 18-19	
N°	Acc	GYH	Acc	GYH	Acc	GYH	Acc	GYH	Acc	GYH	Acc	GYH	Acc	GYH	Acc	GYH
1	A35	108.73	A36	36.29	A16	48.57	A37	83.90	A20	28.86	A02	44.80	A13	33.95	A20	20.34
2	A27	88.85	A38	35.73	A35	47.88	A16	75.02	A33	26.29	A41	38.34	A17	31.64	A29	14.36
3	A14	85.45	A34	30.30	A32	47.48	A04	69.70	A39	26.26	A39	37.01	A31	29.14	A15	12.84
4	A45	83.55	A06	30.27	A34	46.33	A01	68.05	A41	24.85	A13	31.52	A40	28.10	A33	8.99
5	A44	82.13	A39	29.48	A38	45.02	A15	67.63	A02	24.17	A43	30.76	A23	28.03	A04	8.93
6	A18	80.68	A07	28.66	A31	43.20	A11	67.62	A45	21.27	A31	28.38	A42	26.72	A43	8.90
7	A30	76.48	A08	27.60	A10	42.97	A41	67.52	A13	20.88	A08	28.12	A44	26.27	A36	7.67
8	A01	74.57	A10	27.60	A23	42.08	A31	65.40	A26	20.19	A45	27.71	A02	25.89	A13	7.08
9	A40	73.18	A45	26.94	A17	40.98	A06	65.35	A29	19.14	A05	26.44	A26	25.76	A31	6.05
10	A32	73.13	A23	26.65	A25	38.95	A29	65.00	A03	18.90	A33	25.52	A43	24.99	A45	5.74
11	A12	71.22	A22	26.63	A40	37.37	A27	64.45	A44	17.91	A26	24.43	A04	24.09	A28	5.21
12	A03	71.02	A35	25.89	A30	35.53	A38	62.58	A15	15.97	A34	23.94	A15	22.96	A18	5.03
13	A15	70.37	A28	25.40	A29	34.03	A40	61.82	A32	15.69	A44	23.81	A20	22.56	A44	5.02
14	A33	70.12	A13	25.17	A37	31.67	A25	60.72	A01	15.50	A29	21.45	A41	22.29	A03	4.97
15	A05	70.08	A29	25.15	A11	29.85	A03	60.15	A43	15.24	A37	21.07	A33	21.96	A32	4.67
16	A34	69.20	A11	25.03	A28	29.22	A23	59.58	A23	14.85	A42	20.87	A36	21.51	A08	4.62
17	A28	66.58	A44	24.64	A20	29.10	A08	59.35	A11	14.26	A04	20.62	A34	21.42	A16	4.54
18	A06	64.45	A14	24.59	A27	28.98	A12	57.67	A16	14.11	A06	19.67	A05	20.87	A26	4.50
19	A37	64.27	A12	24.14	A01	28.75	A07	57.65	A18	14.04	A32	19.42	A25	20.19	A02	4.44
20	A04	62.23	A02	24.06	A18	27.72	A32	57.58	A07	13.78	A11	19.21	A10	18.53	A30	4.28
21	A08	62.00	A43	23.98	A07	27.60	A22	57.43	A31	12.88	A18	18.26	A32	18.41	A01	3.95
22	A11	59.72	A33	23.63	A45	27.50	A05	56.45	A28	12.86	A07	18.23	A18	18.24	A10	3.77
23	A02	58.83	A18	23.42	A05	27.23	A17	56.33	A05	12.62	A30	17.77	A11	17.45	A34	3.77
24	A43	58.72	A30	23.17	A04	26.85	A45	55.52	A36	12.55	A36	17.65	A45	17.39	A41	3.74
25	A16	58.67	A32	23.14	A22	26.85	A35	54.87	A37	12.31	A16	17.65	A06	17.27	A40	3.72
26	A23	58.08	A05	23.01	A03	25.52	A33	52.88	A34	11.81	A03	17.59	A16	16.87	A37	3.36
27	A07	57.42	A17	22.88	A26	25.48	A14	52.82	A25	11.43	A14	15.80	A29	16.53	A38	3.22
28	A36	55.75	A26	21.63	A36	24.88	A10	50.70	A30	11.03	A23	15.09	A30	16.03	A25	3.16
29	A29	55.27	A27	21.52	A14	24.87	A02	50.42	A38	10.99	A01	14.50	A27	15.87	A11	2.95
30	A25	54.22	A03	21.47	A02	24.40	A44	50.37	A27	10.40	A40	14.13	A03	15.49	A05	2.82
31	A38	53.67	A37	21.36	A12	24.15	A18	50.07	A06	10.30	A10	13.47	A37	14.14	A14	2.81
32	A39	52.95	A16	21.16	A39	22.90	A26	48.87	A08	10.28	A17	13.32	A07	13.85	A42	2.75
33	A20	52.12	A20	21.07	A33	22.18	A34	47.38	A17	10.23	A27	12.64	A39	12.99	A06	2.74
34	A41	49.47	A31	20.57	A08	21.72	A30	46.72	A04	10.04	A15	12.62	A22	10.63	A39	2.46
35	A17	49.12	A40	20.08	A41	19.73	A42	45.82	A14	9.82	A25	12.29	A28	10.30	A17	2.17
36	A31	47.10	A41	19.15	A15	19.20	A39	45.58	A35	9.58	A28	11.77	A12	9.96	A07	1.92
37	A13	45.87	A01	17.92	A43	19.00	A43	42.55	A40	9.14	A20	10.35	A01	9.37	A22	1.90
38	A42	45.28	A42	16.43	A13	18.95	A28	42.33	A10	9.08	A38	9.12	A38	8.97	A12	1.81
39	A10	44.52	A25	15.41	A06	18.85	A20	40.93	A12	8.44	A12	6.39	A14	8.40	A35	1.64
40	A26	41.97	A15	15.23	A44	11.78	A36	39.22	A22	7.96	A35	5.29	A08	6.91	A27	1.37
41	A22	38.83	A04	15.09	A42	9.00	A13	34.87	A42	7.94	A22	2.34	A35	6.23		

In the second-year trial, the early inauspicious conditions for optimum plant growth (December–February) were suitable for genotype discrimination at Bouchane and Tiflet. At Bouchane, lines A20 and A33 were the highest yielding genotypes, 28.86 and 26.29

qx/ha, respectively (Table 8). The exceptionally dry conditions at the Bouchane site are best conveyed photographically; Figure 2 shows conditions on 3 May, approximately one month before harvest, where the *A. magna* plots provided seed when the wheat and barley crops elsewhere on the farm were a complete loss, being plowed under or opened up for livestock grazing. In terms of dry matter yield, line A02 was highest at 43.93 q/ha.

At Tiflet, line A20 recorded the highest GYH, at 20.34 q/ha (Table 8). The highest DYQ was in lines A33 and A41 with a biomass production of 32.93 and 31.14 q/ha, respectively. As with the agro-morphological traits, the lines at the Tiflet site were likely well below their productivity potential due to the poorly managed organic production conditions.

At El Kebab, GYH and HI were higher compared to the other sites. Line A02 produced an average yield of 44.8 q/ha, followed by A41 with a yield of 38.34 q/ha (Table 8). Lines A43, A02, and A44 had the highest harvest indices at 40.52%, 39.23%, and 39.22%, respectively. The grain yield results at the El Kebab site were significantly higher in the second experimental campaign (2018–19) compared to the first (2017–18) because of the improved soil tillage during cultivation, fertilization, and irrigation along with the warmer temperatures and the absence of prolonged cold period.

The Meknes trial was characterized by relatively high biomass production. The DYH reached 179.3 q/ha for line A02 and 133.46 q/ha for A17. The results at Meknes in 2018–19 were lower, though consistent with, those of the previous year in the same region.

The ranking of the genotypes changed from one environment to another. The genotypes yield fluctuation across the locations and years is an indication of the significant effects of the G×E interaction and a differential performance of the genotypes across the environments as well as yield instability between the experimental locations [12].

3.2. Interlocality Analyses

3.2.1. Three-Factor ANOVA's and CV's

Descriptive statistics for the agro-morphological and productivity traits showed different degrees of variation between the parameters (data not presented). BYDV susceptibility rate varied between 0 and 100% with an average of 20% and had the highest variability coefficient (129.56%). The RW presented a high coefficient of variation (119%). The GYH, DYH, DYP, GYP, NGP, and NFT all showed variability ranging from 60-119%. The GYH varied between 0.34 and 164.80 q/ha with a mean of 24.38 q/ha. The thousand-seed weight (TSW) had the lowest CV (27.46%), ranging from 12.50 to 58.49 g with a mean of 35.19 g.

We performed the three-way ANOVAs for the site, line, and block factors. Significant sources of variation are displayed in Table 9. Very highly significant site, line, and their interaction for the 13 agro-morphological traits are shown except for the effect of the accession on plant vigor in the vegetative growth phase. The block factor-related effects were high for PH, RW, and vegetative growth vigor and were not significant for most traits. The accession-block interaction was significant for PH and DYQ (Table 9).

Table 9. Three-way ANOVA for the agro-morphological and productivity traits.

Variable	Site	Accession	Block	Accession*Site	Accession*Block
PH	4456.56 ***	3.99 ***	21.62 ***	2.21 ***	2.39 ***
RL	456.52 ***	2.97 ***	0.7	1.98 ***	1.06
NFT	221.03 ***	3.50 ***	0.362	2.45 ***	1.37 *
RW	129.54 ***	2.65 ***	8.66 ***	2.15 ***	1.00
SW	338.12 ***	2.56 ***	5.46 **	2.66 ***	1.53 **
BP	313.98 ***	2.50 ***	6.68 **	2.55 ***	1.44 **
NGP	52.47 ***	2.04 ***	2.02	1.57 ***	1.38 *
DYP	88.62 ***	2.20 ***	2.49	1.66 ***	1.40 *
GYH	504.23 ***	1.73 **	0.95	2.47 ***	1.59 **

DYH	1181.34 ***	3.68 ***	2.72	2.73 ***	1.62 ***
HI	294.07 ***	2.46 ***	3.01	3.87 ***	1.53 **
TSW	286,247.27 ***	1465.12 ***	0.01	1182.91 ***	0.01
VGV	1558.26 ***	4.721	9.58 ***	2.56 ***	1.25

Explanations: PH = plant height (cm); RL = root length (cm); NFT = fertile tiller number; RW = root weight (g); SW = stem weight (g); BP = plant biomass (g); NGP = number of grains per plant; DYP= dry matter weight per plant (g); GYH = grain yield (q/ha); DYH = dry matter yield (q/ha); HI = harvest index; TSW = thousand-seed weight (g); VGV = growth vigor at vegetative stage. *Significant at $p = 0.05$; **significant at $p = 0.01$; ***significant at $p = 0.001$.

3.2.2. Correlation Matrix

The Pearson correlation matrix values among variables are displayed in Table 10. Significant values are highlighted in bold type. The highest positive correlations of paired variables were observed between DYP and GYP (R = 0.97) and between NGP and GYP (R = 0.93). Other significant positive correlations were observed between GYH and DYH (R = 0.65) and between DYP and RW (R = 0.60). There were also significant correlations with R-values of 0.54 between DYP and GYP; 0.52 between DYP and SW; and 0.51 between DYH and VGV, SW, and DYP (Table 10). The low positive correlations ranged from 0.49 to 0.40 and were observed between NGP and GYP (R = 0.47); NGP and GYH (R = 0.45); TSW and PH (R = 0.41); and HI and GYP (R = 0.40). The lowest correlations were measured between NFT and RL (R = 0.36); NFT and TSW (R = 0.36); NFT and GYP (R = 0.35); NGP and DYP (R = 0.33); and GYH and DYP (R = 0.31). In addition, there were two negative correlations between parameters: the first was between HI and DYH (R = −0.43) and the second between GYP and BYDV sensitivity (R = −0.34).

Table 10. Correlations matrix among variables at the eight experimental sites. *Significant correlations at $p = 0.05$.

	VGV	PH	RL	NFT	GYP	SW	RW	DYP	NGP	GYH	DYH	HI	TSW	CR	BYDV
VGV	1														
PH	0.16	1													
RL	−0.25	0.06	1												
NFT	−0.23	0.23	−0.13	1											
GYP	−0.14	0.22	0.36*	0.35*	1										
SW	0.10	0.28	0.25	0.42*	0.52*	1									
RW	0.05	0.15	0.19	−0.15	0.29	0.39*	1								
DYP	0.09	0.27	0.27	0.33*	0.54*	0.97*	0.60*	1							
NGP	−0.12	0.11	0.29	0.26	0.93*	0.47*	0.27	0.49*	1						
GYH	0.17	0.06	0.24	0.18	0.47*	0.33*	0.03	0.31*	0.45*	1					
DYH	0.51*	0.10	0.19	−0.10	0.02	0.51*	0.28	0.51*	0.03	0.65*	1				
HI	−0.19	−0.09	−0.16	0.20	0.40*	−0.24	−0.22	−0.26	0.50*	0.17	−0.43*	1			
TSW	−0.02	0.41*	−0.04	0.36*	0.20	0.19	−0.02	0.16	−0.07	0.09	−0.04	0.14	1		
CR	0.18	−0.03	−0.26	−0.07	−0.26	−0.14	−0.16	−0.16	−0.26	−0.05	0.08	0.09	0.19	1	
BYDV	−0.18	−0.04	0.10	0.11	−0.34*	0.00	−0.21	−0.07	−0.31	−0.13	−0.01	−0.24	0.02	−0.02	1

Explanations: VGV = growth vigor at vegetative stage; PH = plant height (cm); RL = root length (cm); NFT = fertile tiller number; GYP = grain yield per plant (g); SW = stem weight (g); RW = root weight (g); DYP= dry matter weight per plant (g); NGP = grain number per plant; GYH = grain yield (q/ha); DYH = dry matter yield (q/ha); HI = harvest index; TSW = thousand-seed weight (g); CR = crown rust reaction; BYDV = barley yellow dwarf virus infestation.

3.2.3. Principal Component Analysis

The principal component analyses (PCA) were conducted at three sites (Table 2): Berrechid on the relatively humid central Atlantic Coastal Plain; Bouchane at a semiarid location on the Central Plateau; and El Kebab representing a relatively high-altitude environment in the Middle Atlas Mountains. In addition, we carried out a combined-site PCA.

The Berrechid experiment's first two principal axes' contribution to the total variability was 57.78%; for El Kebab and Bouchane these values were 57.03% and 56.14%, respectively (Table 11). The variables positively correlated to the first principal component in the three locations were GYP, NGP, NYP, and NFT. The GYH, DYH, and SW parameters contributed to the PC1 in two of the three locations. The PH and TSW contributed mainly to the 2nd and 3rd main axes. Unique significant contributions observed were for RW to the PC1 at Bouchane and HI to the PC2 at El Kebab. The variables of the eight experiments that contributed significantly to the first main axis were DYP, SW, GYP, and NGP (Table 11). The second axis correlated with TSW, DYH, VGV, and NGP, and the third main axis to HI, NFT, PH, and RL.

Table 11. Principal component (PC) analysis results from each of three, or eight combined, sites. Values represent precent (%) of variability contributed by each trait at each location for the first two PC's. *Significant values (p = 0.05).

Traits	Berrechid 2018			Bouchane 2019			El Kebab 2018			Eight Sites Combined		
PCs	F1	F2	F3	F1	F2	F3	F1	F2	F3	F1	F2	F3
VGV	0.22	8.65	38.93*	5.09	9.61	3.39	0.06	0.16	27.30*	0.08	12.82*	1.78
PH	1.40	29.66*	6.89	0.96	10.71*	20.32*	7.66*	0.09	1.84	3.00	0.23	14.38*
RL	0.20	4.94	13.86*	4.94	2.84	15.49*	4.71	0.14	16.49*	3.88	0.05	10.64*
NFT	10.41*	0.61	1.03	16.53*	1.14	0.07	7.87*	5.51	0.34	3.46	5.56	17.93*
GYP	14.91*	0.92	0.49	16.50*	0.02	2.25	13.43*	6.97	0.53	16.09*	9.72	0.57
SW	12.39*	9.30	1.77	0.42	22.42*	11.50*	11.31*	6.63	0.83	17.53*	2.46	1.50
RW	9.31	1.57	3.69	15.92*	0.97	4.32	8.77	5.57	0.67	6.16	3.39	4.59
DYP	12.99*	8.88	1.56	14.01*	0.28	1.24	13.44*	8.15*	1.00	18.57*	3.19	0.21
NGP	14.95*	0.69	0.06	12.16*	1.07	1.89	10.76*	7.17*	7.03	13.66*	10.20*	3.75
GYH	11.08*	6.76	9.21	10.57*	5.81	0.05	8.14	15.52*	0.03	8.29	0.06	0.00
DYH	10.76*	1.58	0.10	0.20	16.59*	15.07*	12.22*	2.80	0.06	5.44	21.84*	0.00
TSW	0.91	26.13*	18.60*	2.52	14.79*	4.61	0.99	0.78	40.27*	0.02	27.46*	0.21
HI	0.46	0.32	3.82	0.15	4.53	1.13	0.64	40.52*	3.61	1.05	0.80	31.68*
% var.	42.78	14.84		38.13	18.01		42.09	14.94		27.81	16.33	
Sum%	42.78*	57.62*		38.13	56.14		42.09*	57.03*		27.81	44.13	

The projection of individuals and variables onto the two first main axes using biplots revealed groups of lines with comparable field performance (Figure 3). The Berrechid site biplot (a) shows a first cluster (green) linking lines that performed better in terms of GYH, DYH, NGP, NFT, and RW; these included lines A35, A27, A01, A30 A45, A44, and A14. The second group (blue) highlighted lines that were tall, having intermediate yields, and greater harvest indexes: A18, A05, A36, A03, A39, A43, and A28. The poorest performing lines in Berrechid clustered (yellow) in the opposite ends of the PC1; these were less productive, having low HI and PH. The last group (red)wase revealed at Berrechid to have significant VGV, producing intermediate biomass and low HI values; these included lines A40, A23, A16, A07, A25, and A17. The rest of the accessions performed intermediately well for most of the studied parameters.

In the semiarid and hot environment of Bouchane, the biplot delimited four clusters (Figure 3b). The first group grouped the highest-yielding lines: A20, A39, A33 A26, and A29. The second cluster in yellow grouped together drought-sensitive and poor-productivity lines, including A42, A40, A25, A11, A10, A12, A06, and A17. The two other clusters included lines that showed intermediate agronomical potential; the blue one on the top grouped lines A08, A16, A01, A02, A04, A23, A05, and A15 that had better root systems (RL and RW) and were fairly susceptible to BYDV. The other red group below the biplot center reassembles A35, A14, A18, A22, A30, A27, A38 A34, and A32 lines that have high HI, TSW, PH values and relative susceptibility to crown rust.

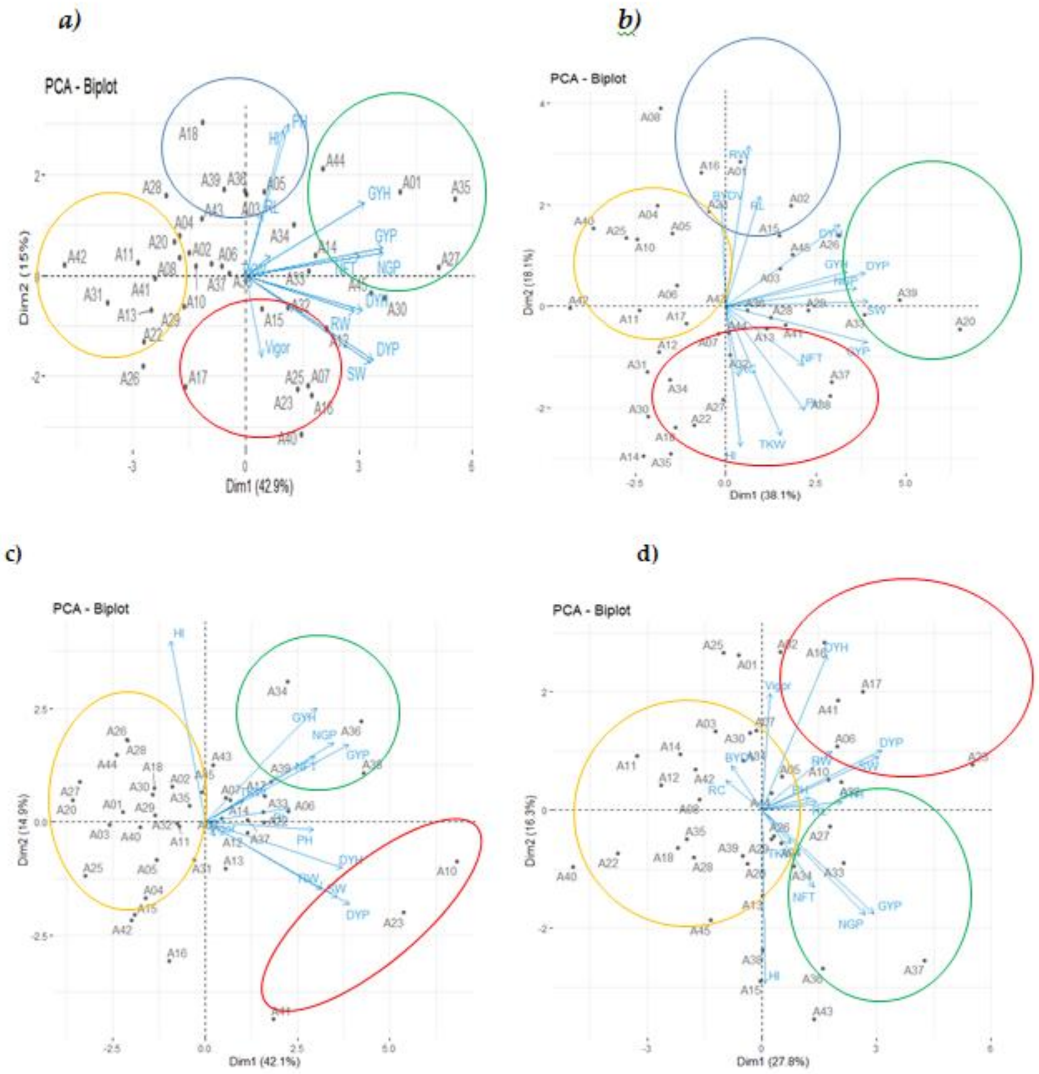

Figure 3. Plots showing dispositions of experimental lines and graphical contributions of variables related to grain yield (GYH) along planes formed by the first two principal components at (**a**) Berrechid in 2017-18; (**b**) Bouchane in 2018-19; (**c**) El Kebab in 2017-18; and (**d**) the combined eight environments.

The factorial plane constructed from axes PC1 and PC2 (Figure 3c) revealed a strong grouping of lines towards the origin of the axis at the high-elevation site of El Kebab. Nevertheless, two distinct groups of experimental lines were evident. The group to the left of the origin (cluster in blue) consists of lines that were generally less productive, while those to the right of the plot were higher yielding. In the El Kebab first-year evaluation, genotypes with the highest grain yields, NGP, and NFT and HI values much higher than those of the experimental lines were A38, A36, A34, A39, A06, A17, A33, A17. Below this cluster, on the negative side of PC2, lines A10, A23, A40 produced more biomass and presented low harvest indices—factors indicative of good potential for ensilage.

The last biplot showing the eight combined experimental trials is in Figure 3d. Each line's potential corresponds to its average performance across testing environments. The green cluster on the positive side of PC1 and the negative side of the PC2 axis grouped lines having high yield potential. In the upper right side of axis 2, the red cluster highlights lines that displayed good biomass potential through their vegetative vigor, high dry matter yield, and root and on-ground vegetation weight. The lines on the left side of PC1 had the lowest productivity and were relatively more sensitive to crown rust and BYDV.

3.2.4. AMMI Analysis

The objective of the AMMI analysis was to accurately characterize the genotype and environmental effects on the productivity and stability of the *A. magna* germplasm across environments. The combined analysis of variance for grain yield of the 41 *Avena magna* lines across the eight environments is in Table 12. The effects of the genotypes, the environments, and their interaction were highly significant ($p \leq 0.0001$) on the total variance. The environment's main effect accounted for 82.89%, whereas genotype and GxE interaction effects accounted for 1.81% and 15.30% of the total variation, respectively.

Table 12. Analysis of variance for grain yield of *A. magna* domesticated lines and its interaction with the environment and AMMI analysis for principal interaction components at the eight testing environments. *Significant at $p = 0.05$; ***significant at $p = 0.001$.

Source	Df	Sum Sq	Mean Sq	F value	Pr (>F)	% Variation
Environment (Site_year)	7	892,679.0	127,526	102.8676 ***	9.34×10^{8}	82.89
Block	12	14,876.0	1240	5.3844 ***	4.28×10^{9}	
G_Line	40	19,467.0	487	2.1138 ***	6.15×10^{-5}	1.81
G×E	279	164,798.0	591	2.5655 ***	$<2.2\times10^{-16}$	15.30
IPCA1	46	22,291.65	484.60	2.1 ***	0.000	47.7
IPCA2	44	14,811.77	336.63	1.46 *	0.026	31.7
IPCA3	42	9587.46	228.27	0.99	0.490	20.5
Error	2568	591,253	230			

The excessive value of the sum of squares of the environment reflected the large differences among testing locations and years (Table 12). Consequently, the *A. magna* lines performed differently across the testing environments. The high percentage of the experimental location effects indicates that the major factor influencing yield was the environment. Even if the genotype factor showed minimal contribution to the total variance for grain yield, it exhibited highly significant genetic differences among domesticated oat lines for grain yield.

In Table 12, the AMMI multiplicative component partitioned the GxE interaction into three interaction principal component axes (IPCAs). The first two axes showed a significant contribution to the GxE in the AMMI model. The first interaction component explained 47.7% of the SCE of the GxE interaction for grain yield. The second axis explained an additional 31.7% of the SCE of the interaction. The AMMI biplot in Figure 4 accounted for 79.4% of the GxE interaction, providing the interaction principal component scores with 90 degrees of freedom.

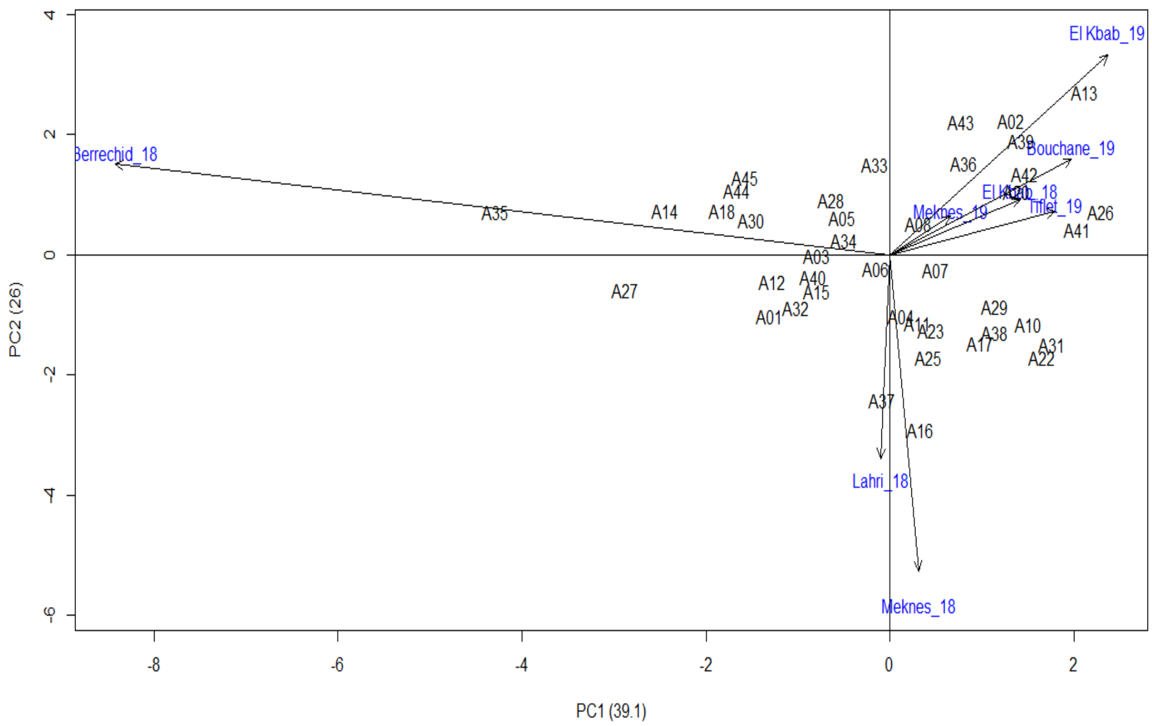

Figure 4. AMMI 2 Biplot of IPCA1 against IPCA2 for grain yield of 41 *Avena magna* genotypes tested across the eight environments.

Genotypes clustering closer to the intersection of the two PC axes tended to be more stable, while those that plotted farther apart from the origin had lower yield stability. According to Purchase [13] and Adugna and Labuschagne [20], the greater the IPCA score (positive or negative), the more adapted a genotype is to a specific environment; conversely, the more the IPCA score approaches zero, the more stable it is. Accordingly, oat lines A35, A13, A27, and A14 were relatively unstable, while lines A06, A08, and A34 displayed high yield stability across environments.

The projection point of a genotype close to an environmental vector indicated specific interaction between both factors. Genotypes A13, A02, A39, A36, and A08 interacted positively at the El Kebab_19 environment. The genotype with the highest positive interaction with Berrechid_18 was A35; A13 interacted positively with El Kebab_19, while A42 had high interaction with Bouchane_19 and A16 was the best genotype in Meknes_18 (Figure 4).

When looking across environments, it is clear that there is tremendous variation among the different experimental locations. Berrechid_18, Meknes_18, and El Kebab_19 showed good potential for discriminating among genotypes, as indicated by their distance from the biplot origin (Figure 4). However, because of their IPCA2 score, the data may not accurately represent their agronomic potential at a specific location. A closer relationship was observed among Meknes_19, Bouchane_19, Tiflet_19, and El Kebab_2018.

Examination of the factorial plane also allowed for the classification of environments according to their average productivity (Figure 5). Thus, at Berrechid_18, line yields were highest, averaging 63.58 q/ha, followed by Meknes_18 at 56.56 q/ha, Lahri_19 (30.42 q/ha), El Kebab_18 (23.94 q/ha), Meknes_19 (20.96 q/ha), El Kebab_19 (20.96 q/ha), Bouchane_19 (14.76 q/ha) and lastly, Tiflet_19 at 5.13 q/ha.

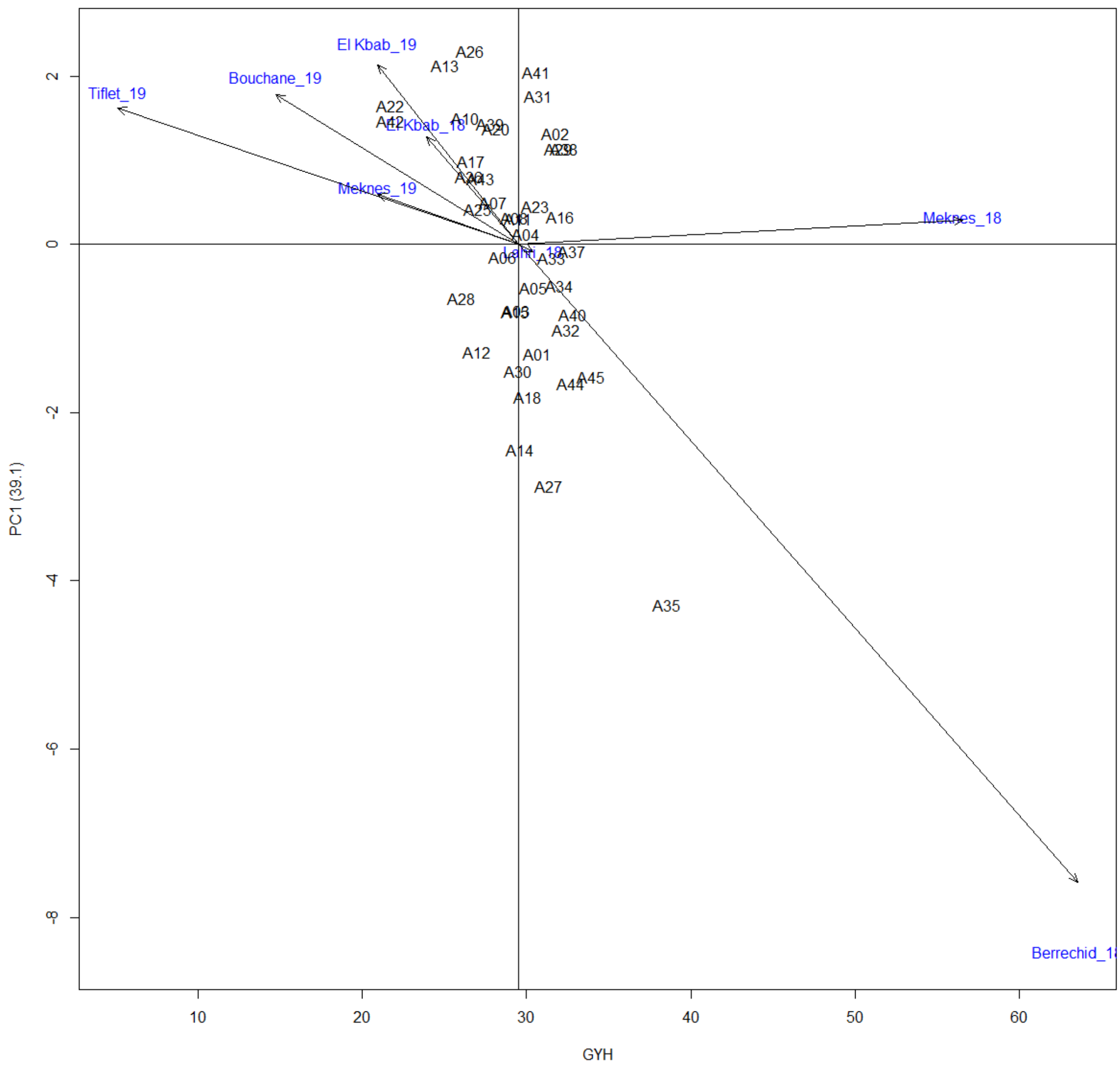

Figure 5. Plot depicting the relationship between AMMI stability (IPC1) and grain yield. IPCA1 (*y*-axis) represents genotype x environment (G×E) interaction plotted against grain yields in q/ha. Values closest to 0 on the *y*-axis represent lines with the greatest stability for yield.

As evidenced by their orientation on the right side of the factor plane, the set of lines including A35, A45, A40 and A37 presented the highest yields of the *A. magna* collection. In contrast, lines A42 and A22, located on the far-left side, were the least productive. However, some of the genotypes with the highest yields were the least stable, including lines A35, A27, A13, and A14.

The factorial plane formed by components PC1 and PC2 provided increased precision for identifying lines that were most yield-stable (Figure 4). Five lines showed good yield stability (ASV ≤ 1) and two among this group had a yield exceeding the average (29.53 q/ha) at all sites: namely, lines A34 (32.02 q/ha) and A05 (30.45 q/ha).

Figure 6 shows the lines ranked according to their grain yield and ASV value across the eight environments. Lines A32, A34, A05, and the control A40 toward the left side of the graph yielded more than the average and exhibited higher stability (low ASV) across environments. Line A35, at the far-right end of the graph, had the highest average yield across the eight environments and the lowest yield stability (highest ASV). Line A45 reached approximately 34 q/ha with an intermediate ASV.

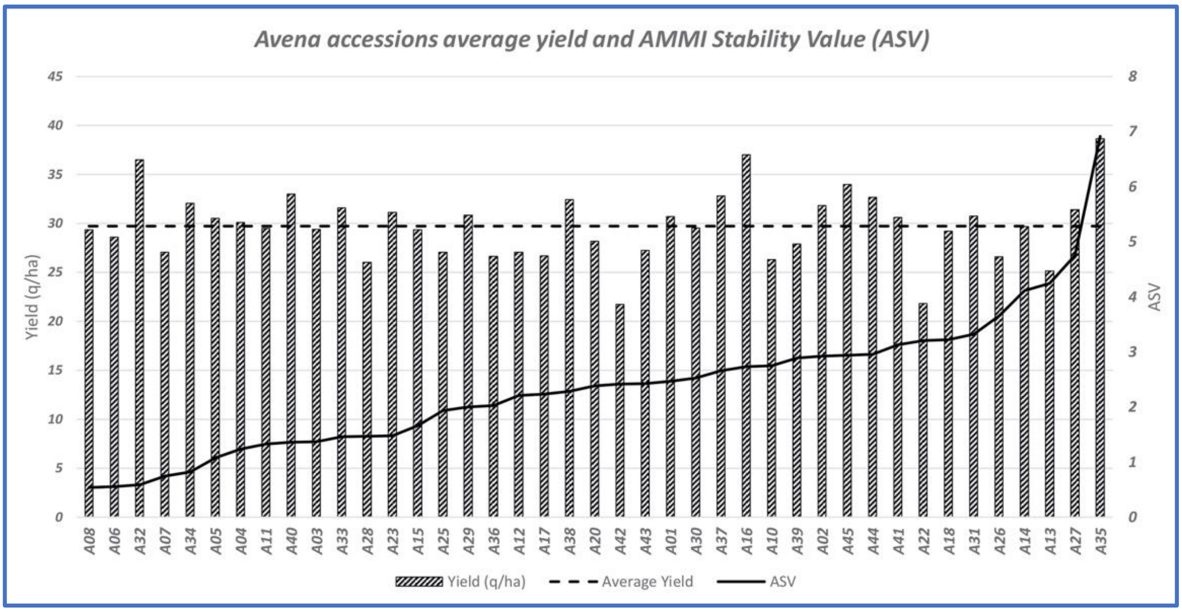

Figure 6. Graph of *A. magna* lines ranked by ASV values (solid trend line) from lowest (far left) to highest, with column heights showing yields in q/ha and average yield across the eight production environments (dashed line).

The graph differentiates four groups with good performance and higher-than-average yield. Group one was the most stable (ASVs < 1) and included lines A32 (32.44 q/ha) and A34 (32.02 q/ha). Group two was moderately stable (1 < ASV < 2) and consisted of five lines: A05 (30.45 q/ha), A40 (32.85 q/ha), A33 (31.58 q/ha), A23 (30.56 q/ha), and A04 (30.01 q/ha). Group three was relatively unstable with ASVs between 2 and 4; it comprised the following 12 lines: A45 (33.93), A37 (32.77), A44 (32.70), A38 (32.34), A16 (32.09), A29 (31.98 q/ha), A02 (31.79 q/ha), A31 (30.72 q/ha), A01 (30.67 q/ha), A41 (30.64 q/ha), A18 (30.09 q/ha), and A14 (29.65 q/ha). Group four consisted of two lines having very high yields but with low stability: A35 (38.57 q/ha), and A27 (31.38 q/ha).

Although the common oat (*A. sativa*) would out-yield the set of *A. magna* experimental accessions, it is important to note that the 108.7 q/ha seed yield of A35 at Berrechid likely represents a substantially higher *seed protein yield* in comparison with any common oat variety, given the previously reported protein content in the Avery check (line A40) of 25.9% versus *A. sativa* at 12.9% [9]. In addition, considering that common oats are known to require more water for grain production than wheat or barley [21] it is remarkable that the *A. magna* accessions at Bouchane included lines approaching 28.86 q/ha (line A20) under a mere 201.5 mm (7.93 in) of ambient rainfall in well-drained soils (Figure 2, Table 2) and without supplementary irrigation—conditions under which surrounding wheat and barley fields did not provide measurable seed yields. Varietal registration trials of check 'Avery' performed in 2019-20 recorded a grain yield of 32.43 q/ha with two supplemental irrigations at El Kebab (unpublished). These results warrant continued efforts to develop *A. magna* as a climate change-resistant crop for human and animal nutrition in vulnerable areas of the subtropical developing world and especially in well-drained soils.

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