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Optimizing hydroponic forage production from Moroccan cereal varieties: nutritional quality, yield and digestibility for sustainable livestock feed

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Abstract: Climate change and natural resource depletion, notably water depletion, pose major challenges to agriculture, particularly in arid regions. Adequate livestock feed is vital to ensuring food security. Hydroponic cultivation offers a sustainable solution to these issues. This study evaluated three Moroccan cereal varieties, barley (*Hordeum vulgare*), soft wheat (*Triticum aestivum*), and triticale (Triticosecale), using an automated hydroponic system. The experiment was conducted under controlled conditions to measure green and dry fodder yields, dry matter content, protein levels, and digestibility using a randomized block design with four replicates per species. Significant variations were found among the varieties for all traits, with several positive correlations. Triticale 'Ain Nzagh' produced a green fodder yield of 320 t/ha, wheat 'Malika' achieved 54.34 t/ha in dry fodder, and barley 'Hespanica' showed a protein content of 20.81%, making these varieties promising for hydroponic feed production. These findings indicate the potential of hydroponics in reducing resource use, such as water and land, while meeting the growing demand for animal feed. Further research is required to assess the economic feasibility of these systems for broader adoption in sustainable agriculture.

Keywords: Sustainable agriculture, Livestock feed, limited resource, fodder production, agricultural innovation, plant protein, improved digestibility.
Abbreviation: LR: Root length (cm); **LS**: Shoot length (cm); **GF**: Green Fodder (T/ha); **DF**: Dry Fodder (T/ha); **M**: Moisture Content percentage; **DM**: Dry Matter Content; **MM**: Mineral Matter Percentage; **PRO**: Proteins Percentage; **PH**: Phosphorus Percentage; **NDF**: Neutral Detergent Fiber Percentage; **ADF**: Acid Detergent Fiber Percentage; **ADL**: Acid Detergent Lignin Percentage.

Introduction

In Morocco, agriculture and livestock are essential to food security, particularly in the context of environmental challenges and population growth. The agricultural sector provides vital sustenance and supports livestock through fodder production, which is crucial for meat, milk, and other animal products (FAO,2023). Agro pastoralism plays a central role in food security, especially for underprivileged households in North Africa (Bereket and Zeremariam, 2013). Ensuring sustainable and high-quality fodder resources is imperative, particularly given the increasing interest in hydroponic systems as a solution for land water scarcity (Ghorbel & Koşum, 2022; Indira el al., 2020).
Hydroponic fodder production is a sustainable alternative to conventional farming, addressing issues related to land use, water conservation, and climate change (Bekuma, 2019). Soft wheat, barley, and triticale have demonstrated potential for hydroponic cultivation owing to their capacity to produce high biomass with significant nutritional value (Cifuentes-Torres, 2020; Rani et al., 2022). In particular, barley has been extensively studied for its yield and nutritional quality (Peer & Leeson, 1985; Fazaeli et al., 2012). However, research on soft wheat and triticale remains limited, despite their promise for hydroponic systems.
In this study, we evaluated the performance of these crops under hydroponic conditions, focusing on biomass production, nutritional value, and digestibility. It also investigates the potential of hydroponic systems to enhance livestock feed

quality, particularly in water-scarce regions (Ghorbel and Koşum, 2022). The economic viability and year-round availability of hydroponic systems, coupled with their reduced water usage, render them attractive solutions for sustainable agriculture (Bekuma, 2019).
Furthermore, the utilization of wastewater as a nutrient solution in hydroponics is an environmentally sustainable approach to modern agricultural challenges such as water scarcity and pollution from chemical inputs (Cifuentes-Torres, 2020). This method also facilitates continuous production and reduces the need for labor-intensive practices such as watering and weeding (Dubey, 2020; Rani et al., 2022). Studies have indicated that hydroponically grown fresh forage is highly digestible (Chung et al., 1989; Islam et al., 2016).
Hydroponic barley fodder can yield 6 to 25 kg of fresh matter per square metre daily, with production estimated to range from 10 to 50 tons of dry matter per hectare per harvest (Al-Karaki & Al-Hashimi, 2012; Al-Karaki, 2011). The dry matter content varied between 8% and 19%. The total nitrogen concentration in hydroponic fodder is 12%-24% dry matter (DM) (Sneath & McIntosh, 2003), with barley typically harvested 6-8 days after sowing containing approximately14% nitrogen (Al-Ajmi et al., 2009; Fazaeli et al., 2012; Morgan et al., 1992). The crude fiber content increases by 61% from 0 to 7 day of germination (Peer & Leeson, 1985), reaching approximately 14.2%. Neutral detergent fibre and acid detergent fiber levels in 6-8 day germinated barley ranged from 31.25% to 35.40% and 14.35% to 17.15%, respectively (Fazaeli et al., 2012), while phosphorus content averages 0.07-0.13% dry matter (Sneath & McIntosh, 2003), reaching approximately 14.2%. neutral detergent fibre and acid detergent fiber levels in 6-8 day germinated barley ranged from 31.25% to 35.40% and 14.35% to 17.15%, respectively (Fazaeli et al., 2012), while phosphorus content averages 0.07-0.13% dry matter (Sneath & McIntosh, 2003).
Despite the advantages of hydroponic systems, research on species such as soft wheat and triticale is still emerging, particularly in comparison with more extensively studied crops such as barley (Fazaeli et al., 2012). This study addresses these knowledge gaps by evaluating the biomass and nutritional value of hydroponically grown triticale, barley, and wheat, thereby providing insights into their potential for improving livestock feed and promoting sustainable agricultural practices.

Results

Detailed statistical analysis of morphological, agronomic, nutritional, and digestibility traits of Barley, Wheat and Triticale in a hydroponic system

In this study, the morphological characteristics, yield performance, and nutritional value of three cereal species (soft wheat, triticale, and barley) cultivated under hydroponic conditions were investigated. Each species was systematically assessed to determine its suitability for hydroponic forage production, with particular emphasis on critical parameters, such as biomass yield, nutrient composition, and digestibility.

Morphological traits across different species in hydroponic system

The analysis of morphological traits, such as root length (RL) and shoot length (SL), revealed a highly significant variation ($p \leq 0.001$) among the studied varieties (Table 2). The results indicated that wheat varieties, particularly Arrehane, with an average root length of 12.10 cm and Kharouba at 10.20 cm, exhibited the longest roots (Table 3, Fig 2). These varieties, which possess more developed root systems, may demonstrate superior capacity to absorb nutrients in hydroponic environments. Shoot length, an indicator of vegetative growth, was greatest in the soft wheat variety Arrehane (14.83 cm), followed by the barley variety Beldi (13.83 cm), and the triticale variety Ain Nzagh (13.67 cm) (Table 3, Fig 2). This robust growth suggests effective adaptation of these varieties to the hydroponic environment, which could potentially result in increased biomass yields.

Agronomic performance of selected varieties in hydroponic culture

Agronomic traits, specifically green fodder (GF) and dry fodder (DF) yields, showed highly significant differences ($p \leq 0.001$) among the varieties studied (Table 2). The Arrehane wheat variety exhibited the highest green fodder yield at 324.53 t/ha, followed by Kharouba at 313.56 t/ha and Malika at 309.57 t/ha, while the Amal wheat variety displayed the lowest at 151.05 t/ha (Table 3). Conversely, the Beldi barley variety exhibited the highest dry fodder yield at 54.34 t/ha and the triticale variety Ain Nzagh (36.89 t/ha), while Malika and Kharouba wheat varieties demonstrated lower dry fodder yields at 16.95 t/ha and 15.45 t/ha, respectively (Table 3, Fig 1). These findings underscore the importance of selecting appropriate varieties to optimize fodder production in hydroponic systems and elucidate their potential for generating usable biomass after desiccation, which is a critical factor for forage storage and preservation.

Nutritional value variations among hydroponically grown varieties

Mineral matter content

The analysis of variance (Table 2) revealed a highly significant difference between the varieties for this parameter ($p \leq 0.001$). The mineral matter content (MM) ranged from 1.99% in the wheat variety Amal to 3.59% in the triticale variety Ain Nzagh (Table 3). Variety Ain Nzagh had the highest median value, indicating its potential for providing a higher mineral intake (Fig 2). These results suggest that varieties such as Ain Nzagh may be preferable when mineral requirements for animal growth and health are elevated.

Table 1. Species and variety information.

Species	Varieties	Breeder	Year of release	Characteristics
Bread Wheat (*triticum aestivum*)	Arrehane	INRA Morocco	1996	Adapted to semi-arid regions
	Achtar	INRA Morocco	1988	Favorable and irrigated areas
	Amal	INRA Morocco	1993	Sub-humid regions and irrigated areas
	Kharouba	INRA Morocco	2010	Late variety favorable, and irrigated areas
	Malika	INRA Morocco	2016	Semi-arid, favorable, and irrigated regions
	Snina	INRA Morocco	2017	Arid and semi-arid areas
Barely (*Hordeum vulgare*)	Beldi	-	Population	Resistance to challenging weather conditions
	Najah	Semillas Battle	2014	Mediterranean growing conditions
	Hespanica	Florimond Desprez	1996	Resistance to drought and the ability to adapt to challenging growth conditions
Triticale (*x-triticosecale*)	Ain Nzagh	INRA Morocco	2011	Resistance to drought and diseases

Table 2. Analysis of variance of morphological, agronomical, nutritional value and digestibility characteristics of three cultivars in hydroponic system.

Source of Variation	Df	Morphological traits		Agronomical traits		Nutrition value					Digestibility traits		
		RL	SL	GF	DF	M	DM	MM	Pro	PH	NDF	ADF	ADL
Variety	9	25.21***	19.85***	12002***	456.5***	130.1***	130.1***	0.997***	36.70***	0.062***	103.3***	43.7***	0.25***
Species	2	72.60***	12.77ns	11145ns	1439.1***	434.3***	434.3***	0.803ns	49.16**	0.147***	162.8**	41.7*	0.92***

Note : Significance codes : '***' <0.001, '**' <0.01 '*' <0.05. Abbreviations: RL, root length (cm); SL, shoot length of (cm); GF, green fodder (T/ha); DF, dry fodder (T/ha); M, moisture content; DM, dry matter content; MM, mineral matter percentage; Pro, proteins percentage; PH, phosphorus percentage; NDF, Neutral detergent fiber percentage; ADF, Acid detergent fiber percentage; ADL, Acid detergent lignin percentage.

Table 3. Mean of varieties under hydroponic system for morphological, agronomic, nutritional value and digestibility traits.

Species	Variety	Morphological traits				Agronomical traits				Nutrition value										Digestibility traits					
		SL		RL		DF		GF		M		MM		DM		Pro		PH		NDF		ADF		ADL	
Barley	Beldi	13.83	b	5.90	h	54.34	a	220.34	f	75.67	j	2.43	h	24.33	a	14.27	f	0.39	h	36.30	d	11.18	f	0.60	e
	Najah	9.17	h	2.58	j	31.90	c	152.54	i	79.33	i	2.82	f	20.67	b	15.85	e	0.39	h	36.20	e	8.23	h	0.62	d
	Hespanica	12.67	d	4.17	i	28.41	d	208.37	g	86.50	g	3.32	d	13.50	d	12.98	g	0.54	f	47.90	a	12.35	e	0.79	b
Triticale	Ain Nzagh	13.67	c	6.83	f	36.89	b	244.27	d	85.00	h	3.59	a	15.00	c	20.81	a	0.68	c	40.30	b	16.52	b	1.26	a
Wheat	Achtar	9.23	g	8.27	e	18.94	e	230.31	e	91.77	d	2.49	g	8.23	g	11.73	i	0.62	e	30.00	h	9.51	g	0.34	h
	Amal	6.57	i	5.93	g	18.44	f	151.05	j	87.87	f	1.99	j	12.13	e	12.67	h	0.46	g	30.60	g	6.84	i	0.29	i
	Arrehane	14.83	a	12.10	a	18.44	f	324.53	a	94.34	c	3.22	e	5.66	h	16.79	d	0.66	d	35.00	f	13.21	d	0.53	g
	Kharouba	11.83	e	10.20	b	15.45	h	313.56	b	94.57	b	3.40	c	5.43	i	20.25	b	0.78	a	36.80	c	14.93	c	0.65	c
	Malika	11.83	e	9.73	c	16.95	g	309.57	c	94.97	a	3.49	b	5.03	j	18.37	c	0.77	b	40.30	b	16.73	a	0.54	f
	Snina	10.10	f	8.47	d	18.94	e	197.41	h	90.40	e	2.27	i	9.60	f	11.12	j	0.62	e	28.00	i	6.27	j	0.26	j

The table values represent (Means), "a, b, c, d, e, f, g, h, i and j" Duncan test. LR, Root length (cm); LS, Shoot length (cm); GF, green fodder (T/ha); DF, dry fodder (T/ha); M, moisture content; DM, dry matter content MM, mineral matter percentage; Pro, proteins percentage; PH, phosphorus percentage; NDF, Neutral detergent fiber percentage; ADF, Acid detergent fiber percentage; ADL, Acid detergent lignin percentage.

Fig 1. Hydroponic forage production unit.

Protein content
ANOVA demonstrated a highly significant difference (p ≤ 0.001) in the protein content among the varieties (Table 2). Protein content is a crucial indicator of animal feed quality, particularly in diets intended for growing and producing animals. The Ain Nzagh variety exhibited the highest protein content (20.81%), whereas Snina displayed the lowest (11.12%) (Table 3). Fig 2 corroborates this trend, illustrating a wide dispersion for Ain Nzagh and emphasizing its superior performance. This finding supports the hypothesis that Ain Nzagh is optimal for maximizing protein intake in intensive feeding systems.

Phosphorus content
ANOVA revealed a statistically significant difference (p ≤ 0.001) among the varieties in terms of phosphorus content (Table 2). The soft wheat variety Kharouba exhibited the highest phosphorus concentration (0.78%), in contrast to 0.39% for the barley varieties Beldi and Najah (Table 3), indicating Kharouba's superior phosphorus provision (Fig. 2). Varieties such as Beldi barley and Ain Nzagh triticale demonstrate excellent dry matter and protein content, whereas Kharouba distinguishes itself in phosphorus content. These findings underscore the significance of variety selection based on specific nutritional objectives, thereby optimizing hydroponic systems to satisfy diverse livestock requirements.

Digestibility traits in hydroponic forage: comparative analysis
Digestibility is a crucial factor in evaluating forage quality as it directly influences the nutritional efficiency of livestock. The parameters related to digestibility included Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF), and Acid Detergent Lignin (ADL).

Neutral detergent fiber
ANOVA revealed a highly significant difference (p ≤ 0.001) between the varieties for NDF (Table 2), indicating that certain varieties had superior digestibility owing to their lower fiber content. NDF serves as an indicator of total cell wall content, encompassing hemicellulose, cellulose, and lignin. Higher NDF values generally indicate lower digestibility because they reflect a greater fiber content that is more resistant to degradation. NDF values ranged from 28.00% for Snina wheat to 47.90% for Hespanica barley (Table 3). Fig 2 shows that the Hespanica barley variety exhibited the highest median digestibility. In contrast, the Snina soft wheat variety had a substantially lower value, indicating its superior digestibility.

Acid detergent fiber
Analysis of variance (ANOVA) revealed a highly significant difference (p ≤ 0.001) among the varieties in Acid Detergent Fiber (ADF) content (Table 2), which quantifies the amount of cellulose and lignin compounds that are more resistant to digestion. Higher ADF values are associated with decreased digestibility. ADF ranged from 6.27% for Snina wheat to 16.73% for Malika wheat (Table 3), demonstrating that the Malika variety exhibited the highest median ADF value, corresponding to lower digestibility (Fig 2). Conversely, Snina and Beldi displayed lower ADF values, indicating a higher digestibility. This finding underscores the preference for varieties, such as Snina when the objective is to produce more digestible forage.

Acid detergent lignin
The analysis of variance indicated a highly significant difference ($p \leq 0.001$) among the varieties in ADL content (Table 2). Acid Detergent Lignin (ADL) represents the lignin content, which constitutes the most indigestible component of plant fibers. The presence of lignin significantly reduced the forage digestibility. Table 3 illustrates that ADL ranged from 0.26% for Snina wheat to 1.26% for Ain Nzagh triticale. The Ain Nzagh variety exhibited the highest median ADL value, indicating

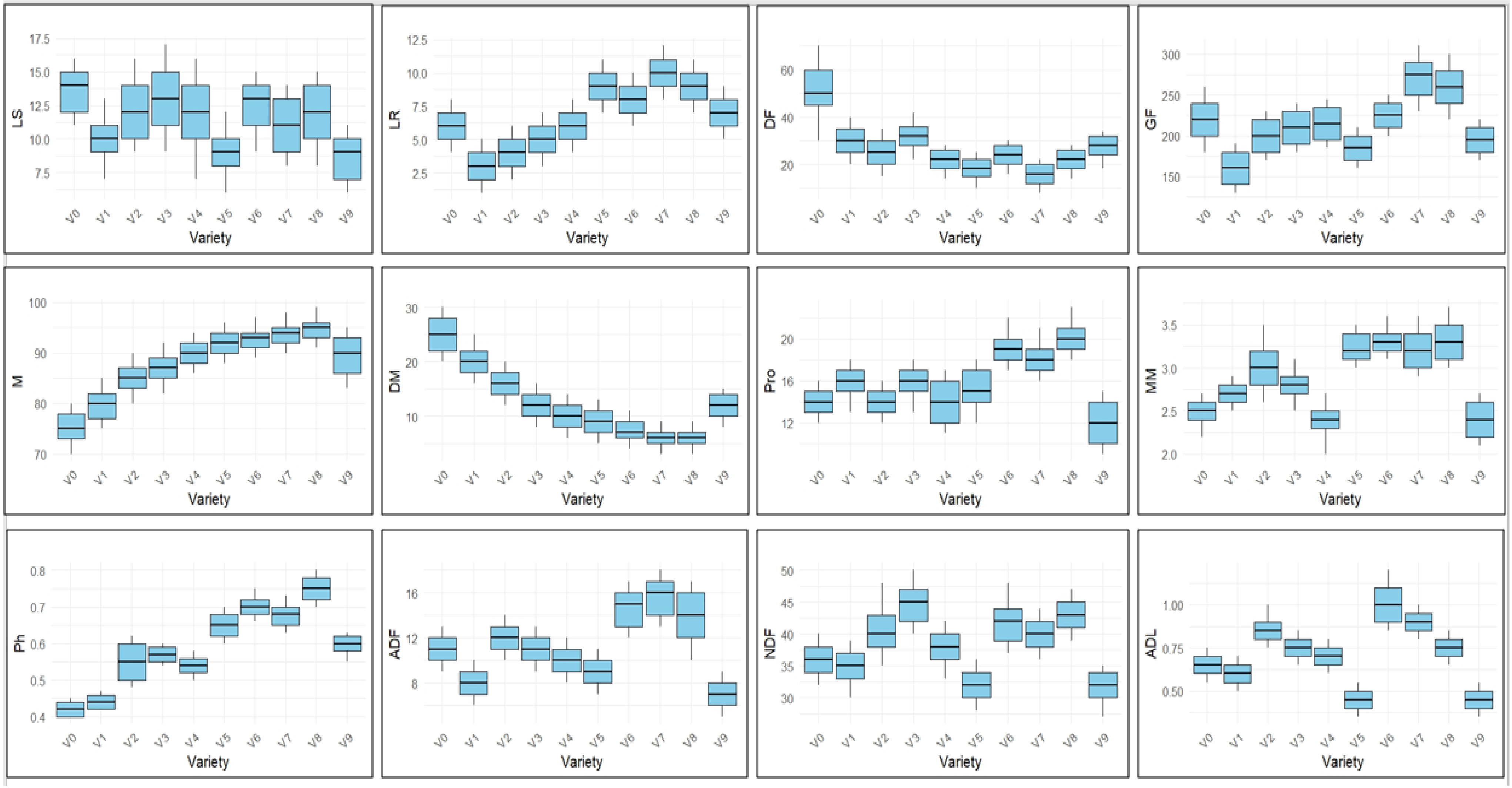

Fig 2. Boxplot comparing the morphological, agronomic, nutritional value, and digestibility traits of hydroponically grown varieties LR, root length (cm); LS, shoot length (cm); GF, green fodder (T/ha); DF, dry fodder (T/ha); MM, mineral matter percentage; Pro, proteins percentage; Ph, phosphorus percentage; NDF, Neutral detergent fiber percentage; ADF, Acid detergent fiber percentage; ADL, Acid detergent lignin percentage; V0, Beldi (barley);V1, Najah(Barley);V2, Hespanica (Barley);V3, Ain Nzagh(Triticale); V4, Achtar (Wheat); V5, Amal (Wheat); V6, Arrehane (Wheat); V7, Kharouba (Wheat); V8, Malika (Wheat); V9, Snina (Wheat).

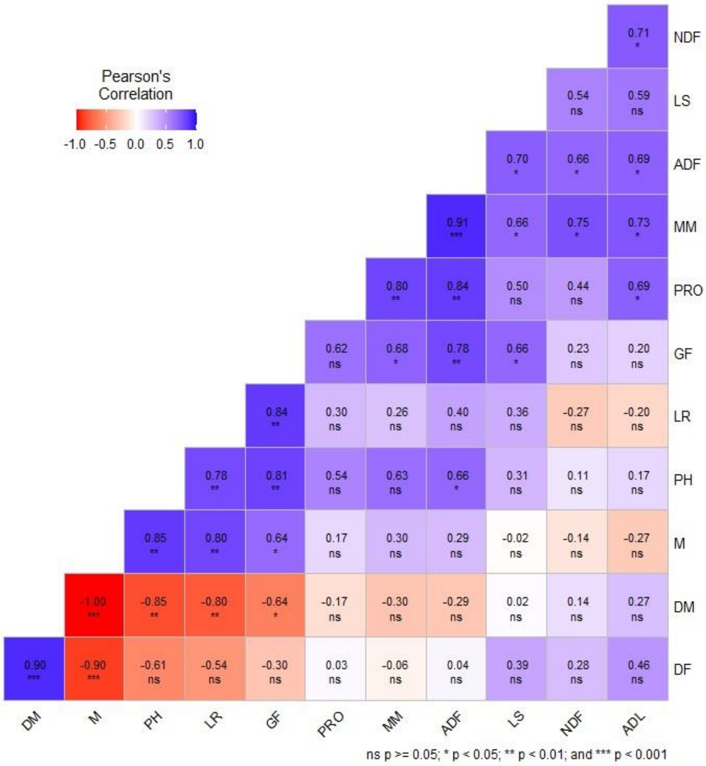

Fig 3. Pearson correlation matrix of variables under hydroponic culture varieties LR, length of root (cm); LS, length of root (cm); GF, green fodder (T/ha); DF, dry fodder (T/ha); MM, mineral matter percentage; Pro, proteins percentage; PH, phosphorus percentage; NDF, Neutral detergent fiber percentage; ADF, Acid detergent fiber percentage; ADL, Acid detergent lignin percentage.

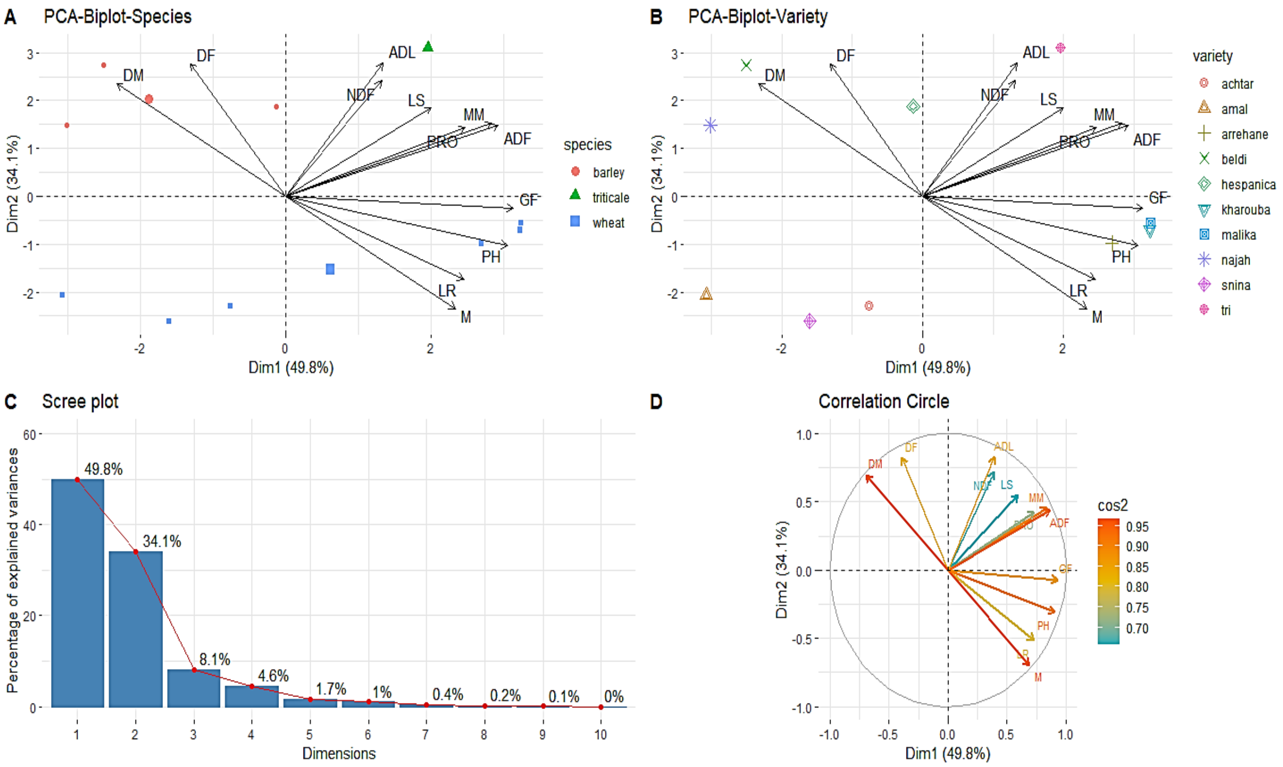

Fig 4 (A-D). Multivariate analysis of the morphological, agronomic, nutritional, and digestibility traits of barley, triticale, and wheat cultivars under hydroponic culture. (A) Principal Component Analysis (PCA) biplot for species (barley, triticale, and wheat) illustrating the relationships between traits and species. (B) PCA biplot for the varieties, demonstrating the distribution of the studied traits across different barley, wheat, and triticale varieties. (C) Scree plot depicting the percentage of variance explained by each dimension of the Principal Components. (D) Correlation circle illustrating the quality of representation of variables (traits) on the first two PCA axes.

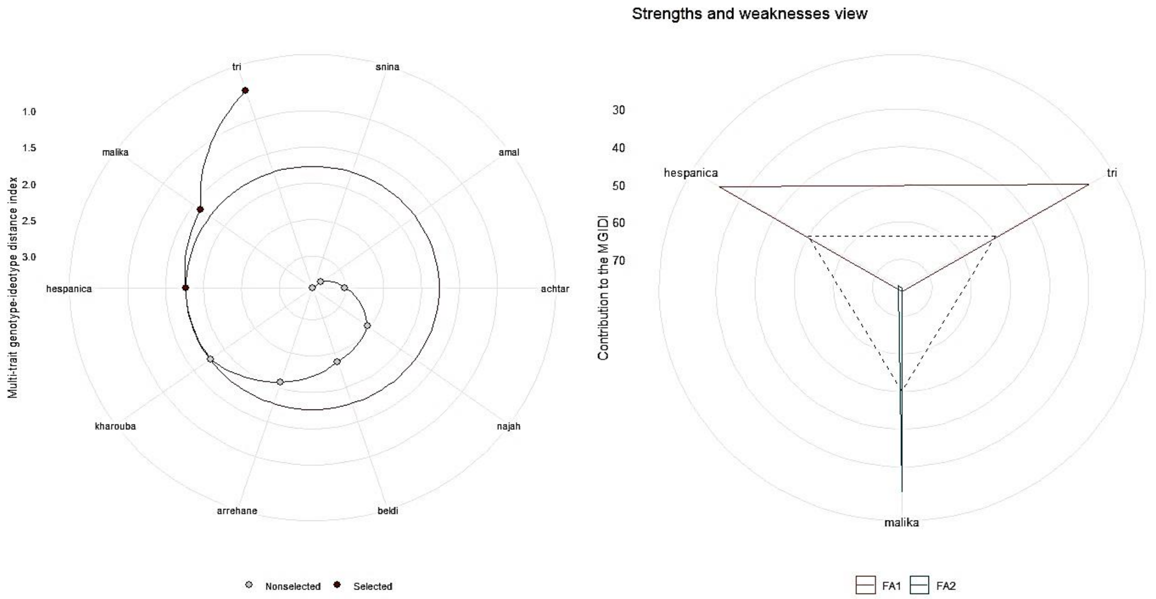

Fig 5. Illustrates the ranking of genotypes using the Multi-Trait Genotype-Ideotype Distance Index (MGIDI) for various traits including green fodder (GF), mineral matter (MM), protein content(pro), phosphorus content (PH), ADF (acid detergent fibre), NDF (neutral detergent fiber), and ADL (acid detergent lignin). The red line represents a selection intensity of 30%, considering the selection of three varieties.

reduced digestibility, whereas the Snina (wheat) and Beldi (barley) varieties displayed lower ADL values (Fig 2), suggesting superior digestibility.

Correlation between different traits

The correlation method was used to examine the relationships between the variables of our study (Fig 3).

We observed a Pearson correlation coefficient of $R^2 = 0.91$ between MM and ADF, indicating a strong positive correlation between them. This suggests that an increase in acid detergent fiber content is generally associated with an increase in mineral content. Similarly, DM and ADF showed correlations of ($R^2 = 0.90$), GF and LR ($R^2 = 0.84$), ADF and PRO ($R^2 = 0.84$), MM and PRO ($R^2 = 0.78$), and GF and ADF ($R^2 = 0.78$). However, the DM variables in relation to PH had a negative correlation coefficient. This suggests that root length has a negative influence on the dry weight of the hydroponic forage.

Principal component analysis

Principal Component Analysis (PCA) of all morphological, agronomic, nutritional, and digestible variables of the hydroponically grown crop varieties (Fig 4). The PCA plots revealed distinct correlation patterns for the studied traits depending on the species (Fig 4A) and variety (Fig 4B). The two principal axes together accounted for 83,9% of the total variation, with PCA1 and PCA2 respectively explaining 49,8% and 34,1% of the total variation traits, respectively, with a higher correlation on PCA1, which strongly contributed to explaining the variability, including green fodder, phosphorus content, acid detergent fiber, mineral matter content, protein content and root length. However, for the second axis, acid detergent lignin, dry fodder, neutral detergent fiber, moisture content and dry matter were observed (Fig 4C). A high cos2 value indicates a good representation of the variable on the main axes of the graph (in this case, the variable is positioned near the circumference of the correlation circle), whereas a low cos2 value indicates that the variable is not well represented by the main axes (in this case, the variable is close to the center of the circle) (Fig 4D).

The Multi-trait Genotype-Ideotype Analysis (MGIDI test)

Multi-trait genotype-ideotype analysis (MGIDI) is used to evaluate different varieties based on the strength of several important traits. The MGIDI test was used to evaluate forage varieties to identify those with high quantity and quality in terms of nutrition and digestibility. The 30% selection pressure indicates the level of importance assigned to each trait analysis, and the decision-making process is influenced by each trait considered in the evaluation.

The selection of traits for evaluation appears well rounded, covering aspects crucial for assessing forage quality and suitability for livestock consumption. High green fodder (GF), mineral matter content (MM), protein content (PRO), adequate phosphorus content (PH), and desirable levels of acid detergent fiber (ADF), acid detergent lignin (ADL), and neutral detergent fiber (NDF) all contribute to the overall nutritional value and digestibility of forage (Fig 5).

Based on the results of the MGIDI test, the Ain Nzagh (triticale), Malika (wheat) and Hespanica (barley) varieties proved to be the best performing, demonstrating desirable characteristics for hydroponic forage cultivation. These varieties offer favorable combinations of characteristics, such as fresh forage yields, optimal mineral and protein content and improved digestibility, making them well suited to meet the nutritional needs of livestock.

Discussion

The arid and semi-arid zones of Morocco encompass 27% of the country and 87% of the arable lands (SAU), contributing to 55% of national production (Mahyou et al., 2010). However, these regions experience water scarcity owing to irregular precipitation, frequent droughts, and soil erosion exacerbated by climate change (Qarro et al., 2010). Traditional practices are no longer adequate, necessitating more sustainable approaches (Mahyou et al., 2010). Hydroponic systems are a promising solution for livestock feed production, with barley, wheat and triticale selected for their adaptability (FAO, 2021). This strategy aims to enhance biomass production, while reducing water and land use.
Wheat, triticale, and barley showed no significant differences in fresh green forage yields, with means of 254, 244, and 194 t/ha, respectively (Ansar et al., 2010). Theoretically, the hydroponic system could produce up to 6350 t/ha/year of wheat and 4850 t/ha/year of barley, assuming 25 harvests per year. Al-Karaki (2011) hydroponically grown barley forage yielded 5600 t/ha/year using tap water. Khlila et al. (2024) reported that the 'Snina' variety yielded 5.49 t/ha in irrigated soil, whereas our hydroponic system produced 7.5 t/ha, a 36% increase. Similarly, the 'Achtar' variety yielded 3.66 t/ha in irrigated soil compared to 5.5 t/ha hydroponically, a 50% improvement. Hydroponics can significantly enhance wheat production, particularly in arid areas.
Hydroponics can substantially boost wheat production in arid regions. Variance analysis revealed significant differences in moisture content across species, affecting the nutritional value, forage digestibility, and dry matter content. Hydroponic wheat had notably low dry matter, while barley and triticale showed higher levels, consistent with Miralles-Bruneau's (2015) findings of dry matter percentages between 10.49% and 32.8% for varieties such as Zeppelin, Arturio, and Forage. Mineral matter levels ranged from 2% to 3.5% for all wheat, barley, and triticale varieties, slightly lower than Benfadel and Mekouar's (2019) 4.3% for hydroponic barley (Saida R1). Final mineral concentrations depend on initial seed levels and germination conditions, and are influenced by watering methods and nutrient solutions (Lennard, 2012). Sneath and Mcintosh (2003) reported hydroponic green forage protein content ranging from 12% to 24% of dry matter, with barley harvested between 6 and 8 days showing approximately 14% dry matter (Al-Ajmi et al., 2009; Fazaeli et al., 2012; Morgan et al., 1992), consistent with our total nitrogen findings. Our data showed higher total nitrogen content than 9.9% to 11.3% protein in grains (Feedinamics, 2021), which is attributed to germination, which triggers physicochemical transformations, enzyme synthesis, and metabolic reactions, enhancing the nutritional properties of sprouted seeds. Enzymes convert starch into simple sugars and synthesize vitamins (A, B, and C) and amino acids, including those absent in dry seeds (Miralles-Bruneau, 2015).
Species disparity in NDF was highly significant ($p \leq 0.001$), with triticale, barley, and wheat showing percentages of 40.3%, 40.2%, and 33.5%, respectively. The differences in ADF content between species were minimal. These findings highlight the superiority of hydroponic barley over dry barley grains, with NDF, ADF, and ADL values ranging from 18.7% to 21.5%, 5.6% to 6.5%, and 1.1% to 1.2%, respectively (Feedinamics, 2021). The increase in fiber content was due to cell synthesis and expansion in young seedlings. As plants mature, fiber content increases, while digestibility decreases, with colder temperatures enhancing NDF digestibility (Lean et al., 2018). The NDF value of hydroponic green forage's NDF value is notable, approaching the desired levels in the overall ration (35-40%).
Barley varieties showed phosphorus rates between 0.4% and 0.5%, slightly higher than the literature-reported values, with dry barley grains having initial phosphorus concentrations of approximately 0.37% (Feedinamics, 2021). The results for triticale and wheat varieties are not comparable to those of previous studies owing to a lack of data. However, compared to dry triticale and wheat grains, the obtained values, except for dry matter percentage, have evolved favorably and even surpassed those of barley varieties.
Through the combined application of ANOVA and Duncan's test for nutritional content and digestibility, several crops have emerged as promising candidates for hydroponic forage production. Triticale is a viable option, exhibiting high dry matter, protein, and phosphorus contents, along with satisfactory digestibility.
Wheat varieties, such as Kharouba and Malika, have similar attributes, featuring high nutrient levels and favorable digestibility. For superior digestibility, wheat varieties such as Achtar, Amal, and Snina are notable for their low fiber and lignin contents, which facilitate livestock digestion.
A systematic approach was implemented to validate the selected varieties against established forage standards. Principal Component Analysis (PCA) was conducted, followed by a Multi-Trait Genotype Ideotype (MGDI) test. These robust statistical methods allow the evaluation of relationships among multiple variables and identification of the most promising varieties (Olivoto et al., 2022).
To enhance reliability and identify varieties with high potential for fresh forage production, the analysis focused on mineral, protein, and phosphorus contents per industry standard. Additionally, fiber digestibility (ADF), lignin content (ADL), and neutral detergent fiber (NDF) content were assessed. A meticulous selection process was conducted, emphasizing that the top 30% of the varieties exhibited the most favorable characteristics.
The results indicated the superiority of 'Ain Nzagh' triticale, followed by the 'Malika' wheat variety, and subsequently the barley variety Hespanica. These conclusions were derived from a comprehensive analysis of forage production parameters and quality standards, enhancing the confidence in selecting optimal varieties to meet specific forage requirements.

Materials and methods

Plant material

In this study, three forage crops were tested with different varieties (Table 1), namely barley (*Hordeum velgare*) with three varieties (Beldi, Najah and Hespanica), wheat (*Triticum aestivum*) with six varieties (Achtar, Amal, Arrehane, Snina, Kharouba and Malika) and triticale (*X-triticosécale*) with variety (Ain Nzagh). Seeds for these crops were obtained from the Institut National de Recherche Agronomique in Settat.

Plant culture and husbandry
A controlled-environment chamber equipped with automated lighting, irrigation, and climate control systems maintained consistent conditions for this investigation. The hydroponic apparatus, featuring a stainless steel framework designed by the OCP community, was installed at the National Agronomy Research Institute, Settat, Morocco. Stainless steel was selected for its structural integrity, longevity, and corrosion resistance, capacity to support substantial loads, ensuring system durability, and minimizing contamination risk (Fig 1). The apparatus comprises two shelving units, each with seven levels (68 cm length, 29.5 cm width, 4 cm height), accommodating 11 polypropylene planting trays per level. Each shelving unit can yield 15-25 kg of green fodder per 8-day growth cycle, depending on crop species, variety, and environmental conditions. The fully automated irrigation system, with four daily cycles, optimizes the transition between misting and drainage and is tailored to the specific requirements of each crop species.

Hydroponic environment
The hydroponic growth chamber was meticulously regulated to optimize the crop growth. The temperature was maintained between 20-25°C, which is optimal for the germination and growth of wheat, triticale, and barley. Relative humidity levels were sustained between 60-70% to prevent desiccation and mitigate conditions conducive to fungal proliferation with sufficient ventilation to regulate moisture. Illumination was provided by 30 W LED lights with a 16-hour photoperiod and 8-hour scotophase, simulating natural daylight essential for photosynthesis. These environmental parameters were continuously monitored and adjusted to ensure a stable and favorable environment for crop development and minimize stress factors.

Plant nutrition in hydroponic system
Forage crops were cultivated hydroponically using tap water alone, without nutrient supplementation, to simulate resource-limited conditions. Tap water, unmodified for pH or nutrients, was administered via automated irrigation cycles to maintain moisture. This methodology facilitates the evaluation of plant growth based exclusively on the nutrients present in the seeds and water, providing insights into their tolerance and adaptability in environments with limited resources, analogous to arid or semi-arid regions.

Preparation of seeds before planting
The seeds were then cleaned to remove any dirt or foreign particles. They were then sterilized for 15 min by immersing in a 10% sodium hypochlorite solution (house bleach) to prevent the growth of pathogens, including fungi that could harm the crop, such as wheat rust (Puccinia spp). This sterilization process is crucial for reducing the risk of fungal contamination in the high-humidity environment of the hydroponic system. To ensure sanitary conditions, planting trays were thoroughly cleaned and disinfected before each growth cycle. After sterilization, the samples were thoroughly rinsed to remove any bleach residue and then soaked in tap water overnight, just over twenty-four hours, to allow for proper hydration.

Once the grains were fully imbibed, they were placed on culture trays and left undisturbed for the entire day. This draining process facilitates the removal of excess water, which can impede germination and lead to degradation. Additionally, draining helps to prevent the development of an overly humid environment that favors fungal growth. After draining, the grains were distributed evenly by hand to ensure the formation of a uniform fodder mat, which was important for consistent growth following germination.

Setting up in the growth room
After grain imbibition, the previously saturated grains were placed on culture trays and left undisturbed for the entire day. This process is referred to as draining. This facilitates the removal of excess water, which can impede germination and lead to degradation. This stage also aims to prevent the development of an environment that could facilitate the growth of fungi that could harm crops. Grain distribution by hand is necessary for the formation of a uniform fodder mat after germination (Fig. 1).

Eight days after seeding, when the fodder biomass was ready to be harvested, the experiment was terminated. For later bromatological tests, detailed data were documented for each tray during the harvesting procedure. The ratio of generated green forage to the weight of the seeds that were originally planted was included in this dataset, along with the total yield of both fresh and dried forage. Furthermore, studies have been carried out to evaluate the nutritional value and digestibility of forage.

Plant measurements
Several morphological characteristics, including shoot height, root length, and leaf length and width, were measured before harvest. The growth of several studied species and variations were compared using these data. To ensure that green forage satisfies the hygiene and quality criteria necessary for its use in animal nutrition, it is crucial to conduct an independent visual assessment of the feed. Weighing the grass mat after harvest enables the calculation of the cycle yield, enabling the evaluation of weight variations for every plot. The dry Matter (DM) concentration was determined at the time

of sampling as part of the bromatological investigations. Two fractions of mineral matter (MM) content (organic and inorganic) were evaluated, and the Kjeldahl method was used to determine the total nitrogen content (Pro). Neutral detergent fiber (NDF) is determined by employing detergents in a neutral and buffered environment, whereas acid detergent lignin (ADL) is separated from the residual ADF by treating it with strong sulfuric acid. Finally, colorimetric analysis was used to estimate the total phosphorus concentration (Ph) by reacting the mineralized and distilled sample extract with vanadomolybdic reagent to yield a yellow color with vanadomolybdic reagent.

Experimental design and statistical analysis

This study used an experimental design based on a randomized complete block with four replications. Species and variety were the factors studied. This study aimed to evaluate and compare various cultivars with respect to their growth and feed value. Using R software and the "agricolae" package, the collected data were statistically analysed using descriptive statistics and two-way analysis of variance on the observed variables, with species and variety as factors (Mendiburu, 2019). Using the "agricolae" software, Duncan post-hoc tests were used to examine differences between the different light intensity treatments that were investigated (Mendiburu, 2019). The "metan" tool was used to do correlation analysis (Olivoto & Lùcio, 2020). A main component analysis was carried out using the R package "factoextra" to gain a better understanding of how variations affect the qualities under study (Kassambara & Mundt, 2017). A multi-trait genotype-ideotype analysis (MGIDI test) was performed using the R package "metan" in order to identify the varieties with superior attributes (Olivoto & Lùcio, 2020).

Conclusion

In conclusion, hydroponic farming has emerged as a contemporary and efficient approach to address nutritional requirements while simultaneously reducing farmers' dependence on water and rainfall and sustaining livestock feed production. The findings of this study indicate that species such as triticale, wheat, and barley varieties Malika and Hespanica have potential as viable options to meet the increasing demand for animal feed. Their nutritional properties and digestibility were rigorously evaluated, thereby substantiating their potential for high-quality forage production. These findings have promising implications for sustainable agriculture by offering a feasible solution to minimize the utilization of limited resources, such as water and arable land, while addressing the growing demand for food security. Consequently, it is imperative to promote and implement innovative agricultural practices such as hydroponic farming to ensure environmental resilience and economic viability in drought-affected regions.

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Authors' Contributions

The authors contributed the following to the study and preparation of this manuscript: I.K. was responsible for Writing - Original Draft Preparation and Data Visualization; A.B. was responsible for Project Administration, Supervision, and Resource Provision; M.M. contributed to Statistical Analysis; O.H. contributed to Study Validation; M.K. was responsible for Methodology and Study Validation; M.S. was responsible for Methodology and Study Validation; and A.A. was responsible for Writing - Review and Editing, Supervision, Data Curation, and Resource Provision. All authors read and accepted the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest

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