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Evaluation and Structuring of Agrodiversity in Oases Agroecosystems of Southern Morocco

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Abstract: Oases play a crucial role in human societies and the conservation of biodiversity, especially in harsh environments like arid zones. They serve as sanctuaries for agrodiversity, preserving diverse agricultural resources under challenging climatic conditions. However, these agroecosystems are becoming increasingly vulnerable to climate fluctuations, droughts, and other environmental changes. Understanding these unique agroecosystems is essential for developing effective strategies to protect them. Agrodiversity serves as a key indicator of the overall health of traditional agroecosystems. To assess the richness and diversity of agrodiversity, field surveys were conducted in six representative oases in southern Morocco. Within each oasis, we interviewed 20 farmers in five *ksour*. Our findings confirm the widespread practice of polyculture and reveal significant diversity among the oases. A total of 55 crops were identified, consisting of 183 varieties. Specifically, the oasis of Tata employed 42 crops, Alnif had 41 crops, Guelmim had 38 crops, Aoufouss had 32 crops, Rich had 29 crops, and Zagora had 28 crops. The profiles of varieties clearly distinguish between *ksour* and oases, highlighting the unique identities of each oasis. The modernization of farming practices is influenced by factors such as farm size, plot fragmentation, dispersal, and irrigation methods. However, its consequences are concerning. There is a risk of losing agrodiversity and compromising the food security of local populations. The shift from household consumption crops to cash crops has negative implications for the availability of diverse and nutritious food. Moreover, modernization often leads to increased water consumption, further straining the already limited water resources in these oases.

Keywords: oasis; southern Morocco; agrodiversity; local varieties; agroecosystem; vulnerability

Citation: Houssni, M.; Kassout, J.; El Mahroussi, M.; Chakkour, S.; Kadiri, M.; Ater, M.; Petrisor, A.-I. Evaluation and Structuring of Agrodiversity in Oases Agroecosystems of Southern Morocco. *Agriculture* **2023**, *13*, 1413. https://doi.org/10.3390/agriculture13071413

Academic Editors: Nunzia Cicco and Adriano Sofo

Received: 27 June 2023
Revised: 13 July 2023
Accepted: 15 July 2023
Published: 17 July 2023

1. Introduction

Historically, oases have served as significant centers of agricultural production and trade [1]. They possess immense potential in terms of cultural wealth and genetic resources [2]. Oases provide valuable ecosystem services and deliver important socio-economic benefits to oasis populations [3]. These services encompass various aspects, including provisioning services related to food, date production, date by-products, and health benefits. Additionally, there are regulating services that involve gas emission regulation, disturbance mitigation, biological and climatic regulation, as well as soil protection against erosion. Supporting services include providing habitats and refuge for wildlife, pollination, carbon sequestration, and soil formation/retention. Lastly, cultural services emanate from all the aforementioned services [3–7]. Traditional oasis agriculture has played a significant socio-economic role throughout history [8]. In Saharan regions, oasis agriculture primarily revolves around cultivating the date palm (*Phoenix dactylifera* L.), which serves as the keystone species in the agroecosystem [9,10]. Other crops are also grown alongside date palms to form the oasis agroecosystem [11]. The oasis agroecosystem represents an intensively cultivated artificial space within a desert environment or an area heavily impacted by aridity. Its fertility is owed to the presence of water and human effort [12,13]. The oasis is characterized by garden-like settings, predominantly consisting of date palms, as well as diverse intercropping [14]. It has facilitated the settlement of local populations in water-scarce, arid environments, with their economy centered around date marketing [15,16]. The oasis cropping system has developed adaptive strategies to overcome environmental constraints and socio-economic changes [10]. One of these strategies involves organizing and structuring the agroecosystem into three substrates [17–19]. The first substrate, known as the upper substrate, consists of date palms that provide protection for the lower crops against wind and sun [20–22]. The second substrate, referred to as the intermediate stage, comprises fruit trees such as olive, pomegranate, fig, apricot, plum, and others [23]. Lastly, the third substrate, known as the lower stage, consists of ground crops including cereals, alfalfa, and vegetables [24–26].

In North Africa, oasis agroecosystems cover approximately 380,000 hectares [27], which represents about 32.4% of the oases in the MENA region [28]. In Morocco, oases span an area of 48,000 hectares and are inhabited by over 1.7 million people within a total land area of 115,563 km^2, resulting in a population density of 15 inhabitants per km2 [29]. These oases are dispersed throughout the southern territory of the country, located south and east of the Atlas Mountains, and encompassing the Anti-Atlas, as well as the valleys of Draa, Ziz, Ghris, Guir, Toudgha, and Figuig [30]. Recognizing their significance as indigenous systems, the oases in southern Morocco were designated as a biosphere reserve (RBOSM) by UNESCO in 2000.

Moroccan oases, similar to their counterparts in North Africa, are undergoing significant transformations that pose a threat to the sustainability of these agroecosystems [23,31]. One of the major challenges is the aging of farmers due to the migration of young people to larger cities or abroad [23]. From an environmental perspective, these agroecosystems are vulnerable to issues such as siltation, water resource deficits, and the salinization of both water tables and soils [32–34]. Moreover, the palm groves face a direct threat to their integrity from the cryptogamic disease called *Bayoud* (*Fusarium oxysporum* F. sp. Albedinis) [17,18,35,36]. From a socio-economic standpoint, the subsistence nature of agriculture necessitates the diversification of economic activities through the development of new income sources, including tourism and the promotion of local handicrafts and products [19,37]. On a global scale, climate change poses a major threat to the sustainability and very existence of oasis agroecosystems [5,18]. North African oases are expected to face significant consequences from the effects of climate change [27]. Current projections indicate a considerable decrease in precipitation, alongside rising temperatures and more frequent extreme weather events [18,38–40]. Consequently, these changes will impose formidable conditions for oasis agroecosystems [41]. Additionally, the increased drought resulting from climate change is likely to impact agricultural activities and productivity within these agroecosystems, which heavily rely on rainfall as their primary water source [27].

The array of threats presents a worrisome outlook for the sustainability and longevity of oasis agroecosystems. Within this context, it is crucial to evaluate the consequences of losing traditional agricultural knowledge and depleting plant genetic resources, which are essential components of agrodiversity. Oasis agrodiversity, in addition to its value as socio-ecological heritage, serves as a crucial pillar for promoting sustainable agriculture through local products. While numerous studies have been conducted on Moroccan oases agriculture, most of them have focused on specific crops or agricultural practices [26,32,42–51], thus showing less interest in the richness of species found [52]. However, there is a clear dearth of studies on oasis agrodiversity in Morocco [18]. In fact, Andriamainty fils et al. (2002) [53] noted that only 30% of the research conducted on Moroccan oasis agriculture primarily focused on date palms, with 20% concentrating on livestock, 18% on irrigation, and 10% on sand and desertification. In contrast, other oasis countries have carried out several studies to assess the status of agrodiversity. Previous studies have made it possible to assess the specific richness of oases and provide the number of crops and varieties grown, for example, in Tunisian oases [9,10], as well as Libyan [54,55], Egyptian [56,57], Omani [52], and Chadian oases [58].

The primary objective of this study is to address the knowledge gap regarding the agrodiversity of Moroccan oases. The study aims to assess the richness and diversity of this component through surveys and field explorations conducted in six oases located in southern Morocco. Additionally, the study will collect data on farm organization, land use, and agricultural practices. A comprehensive assessment of the state of agrodiversity, its organization, and the factors influencing its variation will be conducted. Consequently, the findings of this research will establish a valuable database that can serve as a reference in this field and contribute to the development of strategies for conserving this heritage.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted in six oasis regions spanning a NE–SW gradient. These oases serve as representative examples of the agro-ecological diversity found in the oasis areas situated on the southern slopes of the High Atlas and the foothills of the Anti-Atlas (Figure 1, Table 1). One of the oases, called Rich Oasis, is located in the Midelt province in the eastern High Atlas. Rich is inhabited by a population of 25,992 individuals, exhibiting an average growth rate of 2.58% [59]. Rich Oasis is situated amidst mountains, with the Ziz River running through it from the northwest to the southeast, along with one of its tributaries, the Ziddat River. The oasis experiences irregular rainfall, averaging with an average of around 102 mm annually, but ranging between 60 mm and 220 mm. Due to its elevated location, there is a risk of frost occurring between the months of December and April [60].

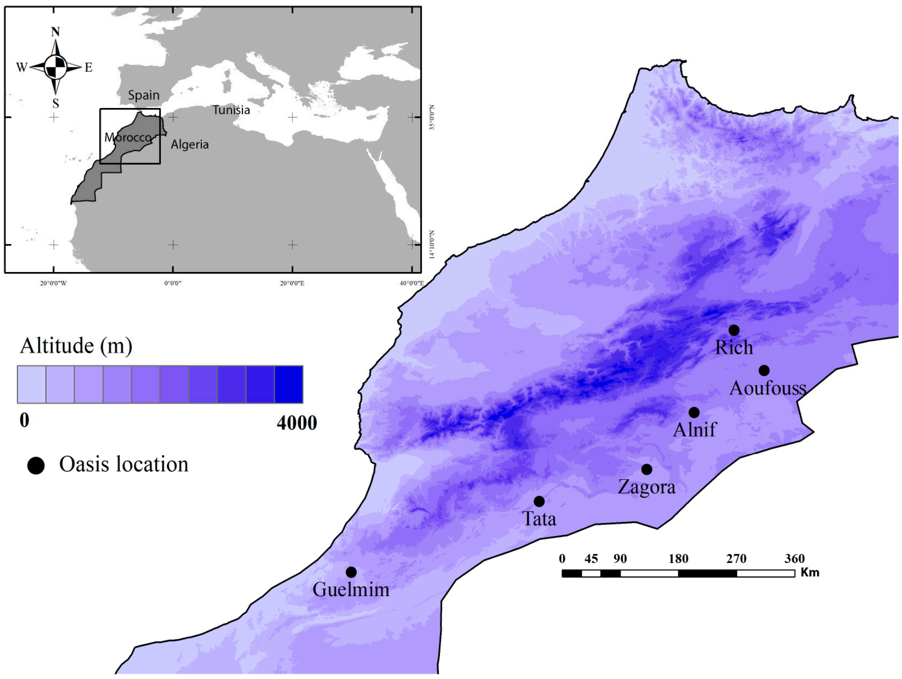

Figure 1. Geographical position of the six studied oases of Rich, Aoufouss, Alnif, Zagora, Tata and Guelmim.

Table 1. Data on the surveyed oases of southern Morocco. The table displays their geographical positions and details, and their administrative status.

Oasis	*Ksour* (Villages)	Area Size (Km^2)	Latitude	Longitude	RM, UM/Cercle	Province	Elevation (m)
Alnif	Ammar	1820	31.182206	−5.229196	Alnif	Tinghir	932
	Tizi		31.138388	−5.202424			917
	Alnif		31.116562	−5.166527			878
	Achbarou		31.149416	−5.087124			844
	Ait Zeggane		31.111649	−4.980195			799
Zagora	Asrir N'ilemchane	46	30.33672	−5.825476	Zagora	Zagora	731
	Tansita		30.362449	−5.8259			724
	Amazrou		30.303602	−5.82218			717
	Sart		30.29751	−5.814578			721
	Aghla Oudrar		30.293483	−5.795879			715
Aoufouss	Takhyamte	32.53	31.687116	−4.191626	Aoufouss	Errachidia	901
	R'bite		31.651772	−4.189161			882
	Zrigate		31.65472	−4.206368	R'teb		883
	Lamâarka		31.639449	−4.21474			879
	Zaouia Jdida		31.616229	−4.22628			866
Rich	Ait Moussa Ouali	513	32.240946	−4.664932	Sidi Aayad	Midelt	1391
	Balite		32.23375	−4.692835			1412
	Zaouia Sidi Boukil		32.235265	−4.726418			1433
	M'zizel		32.245757	−4.7355	M'zizel		1450
	Tamagourte		28.942023	−9.93825			1464
Guelmim	Tighmert	46,108	28.881966	−9.723041	Asrir	Guelmim	797
	Ifrane		28.990686	−9.832463	Ifrane		795
	Fask		29.123409	−9.78502	Fask		343
	Tagante		29.057517	−9.430282	Tagante		550
	Taghjijt		29.90066	−7.320467	Taghjijt		580
Tata	Tissint	25,925	29.235244	−8.536362	Tissint	Tata	681
	Akka		30.095013	−6.88247	Akka		555
	Ait Oubelli		29.910027	−7.333354	Ait Oubelli		493
	Foum Zguid		31.182206	−5.229196	Foum Zguid		650
	Foum Lahcen		31.138388	−5.202424	Foum Lahcen		478

The Aoufouss Oasis is situated within the Errachidia province, encompassing two rural communes: Aoufouss and R'teb. It is located 40 km away from the city of Errachidia [61]. The oasis experiences a semi-arid climate characterized by low precipitation, not exceeding 100 mm per year. Temperature fluctuations range between extremes, with winter temperatures reaching as low as −5 °C and summer temperatures reaching up to 40 °C [61].

The Alnif Oasis is located in the rural municipality of Alnif within the Tinghir province. Geographically, it is situated in the eastern Anti-Atlas and serves as a crossroads for three provinces: Errachidia, Ouarzazate, and Zagora. The climate is classified as Saharan with a continental tendency, predominantly influenced by Saharan air masses and sporadic southwest Atlantic influences. Annual rainfall does not exceed 80 mm, and summer temperatures can reach 45 °C [62].

The Zagora Oasis is located within the Draa Valley and administratively falls under the Drâa-Tafilalt region. The climate is classified as Saharan, with mild winters and scorching summer temperatures surpassing 48 °C in July and August. Winter temperatures hover around freezing point in December and January. The average annual rainfall is 74 mm [63].

The Tata Oasis is situated in the Tata province within the Souss-Massa region. The population is approximately 114,758 inhabitants [64]. Due to its location in a pre-Saharan region, Tata Province experiences a continental Saharan climate, with summer temperatures reaching 49 °C and winter temperatures averaging around 12 °C [64]. Annual rainfall rarely exceeds 100 mm, and the water resources primarily consist of wadis and groundwater. Floods play a significant role in agriculture, contributing to the renewal of the water table.

The Guelmim Oasis is located within the Guelmim province and falls under the Guelmim-Oued Noun region. Minimum and maximum temperatures range between 4.5 °C and 6.4 °C and between 27.9 °C and 27.0 °C, respectively [64]. The wettest season typically occurs from mid-October to the end of February. The total population of the region is approximately 414,489 inhabitants, with a density of 8.25 inhabitants/km^2. Nearly half of the population resides in the Guelmim province, totaling 186,832 inhabitants [59].

2.2. Data Collection

We employed a survey technique that has been utilized in previous studies to assess and inventory oasis agrodiversity [65,66]. Data collection spanned almost 3 years and two periods. The first period lasted two years, from May 2015 to May 2017, during which the study was carried out in four oases in southern Morocco: Rich, Aoufouss, Alnif, and Zagora. The second period lasted one year, from April 2018 to April 2019, during which surveys were conducted in two additional oases: Tata and Guelmim. The surveys were conducted using a semi-structured interview technique based on questionnaires (see Supplementary Material, Supplementary S1 for details). Active farmers within the oases were the target respondents for these surveys. We established the socio-economic profile of the participants by collecting data on age, marital status, level of education, and secondary activities. In each oasis, we conducted the surveys in five *ksour* (plural of *ksar*, fortified village; the term also designates all its inhabitants) per oasis, interviewing a sample of 20 farmers per *ksar*. In total, 600 individuals were surveyed. The questionnaires were designed to gather not only individual data, but also: (i) information about the cultivated crops, including the names of varieties, their origin, and vernacular names (in Arabic or Berber); and (ii) details about the cultivated area, number and average size of plots, land characteristics, agricultural practices (such as sowing, tilling, harvesting, threshing), as well as water supply and machinery methods. For this study, we considered both traditional local varieties [67] and recently introduced selected varieties.

2.3. Data Processing and Statistical Analysis

The quantitative and qualitative data obtained were grouped and organized in an Excel database. Microsoft Office Excel 2007 was used to calculate the means and frequencies of the parameters. For the diversity indices, we employed the varietal or crop richness, which represents the number of identified varieties or crops within an oasis. Shannon's diversity index (H') (1948) [68] ($(H' = \sum_{i=1}^{S} p_i log_2 p_i)$) quantifies diversity by considering both the number of crops or varieties (S) and their abundance (pi). It ranges from 0 to 5. The equitability index (E') by Piélou (1966) [69] ($(E' = H'/log\ (S))$) assesses the distribution of crops and varieties, regardless of richness [70], with S representing the number of crops or varieties and H' representing the Shannon index. This index ranges from 0 to 1 and is particularly useful for comparing samples with different levels of richness or comparing different types of ecosystems [71]. The calculations were performed using the R software [72] with the Vegan package [73].

To assess the structure of agrodiversity and the classification of the studied oases, we conducted a Principal Component Analysis (PCA) and a Factorial Correspondence Analysis (FCA). These methods were chosen due to their ability to compare the empirical dimension of the factors with the three dimensions [71]. The PCA was conducted using data on agricultural practices, while the FCA was based on the presence/absence data of all surveyed varieties and crops. These analyses were performed using SPSS version 20 software (IBM Corporation) and R software [72].

3. Results

3.1. Crop Diversity and Varietal Richness

Agrobiodiversity encompasses the biodiversity found within agricultural systems, including all species involved in agricultural production. In this study, we assessed agrodiversity at two levels: (i) the specific level, which focused on the diversity of cultivated crops by conducting an inventory of the species grown, and (ii) the varietal level, which examined the diversity and abundance of varieties within each cultivated crop. It is important to note that the term "variety" is not used strictly in a taxonomic sense, referring to entities listed in catalogs, but rather as entities recognized and named by farmers, representing local traditional knowledge. The conducted surveys revealed significant richness in terms of both the number of crops cultivated and the varieties utilized by farmers (Supplementary Material, Table S1).

The total number of crops identified across all studied oases was 55, classified into six categories: vegetables (20), fruit trees (17), cereals (6), pulses (5), spices (5), and forages (2). The distribution of crops among these categories is relatively consistent across the different oases. Vegetable crops exhibit the highest diversity, followed by fruit trees, collectively accounting for over 70% of the cultivated crops. The abundance and diversity of crops highlight the significant role of polyculture as a defining characteristic of oasis agricultural systems. Fodder crops, primarily alfalfa with the recent introduction of forage sorghum in some oases, are fundamental crops that underscore the importance of livestock within the oasis production system. The substantial level of polyculture, both in terms of diversification across crop categories and crop types within each category, in relation to the size and number of cultivated plots, unequivocally signifies the predominantly subsistence nature of agriculture in most cases.

Crop diversity varies significantly between oases, with Tata and Alnif exhibiting the highest richness with 42 and 41 crops, respectively, while Zagora practices a narrower range with only 28 crops (Figure 2). However, crop richness alone does not adequately capture the diversity of crops, as it overlooks the relative abundance of each crop. Therefore, the application of the Shannon–Weaver diversity index (H′) proved to be valuable. Comparing the H′ indices among the different oases reveals a variability in diversity, albeit within a narrower range compared to crop richness, ranging from 3.5 in Tata to 2.9 in Zagora.

In general, an H′ index value equal to or greater than 3 is considered indicative of a substantial level of diversity [74]. Conversely, the equitability index (E′) is relatively low, ranging from 0.08 in the most diverse oases to 0.14 in the Zagora Oasis. This implies that despite the overall richness of crops, a small number of staple crops are widely cultivated, while the remaining crops are grown by a limited number of farmers.

This observation becomes evident when examining the relative importance of crops within each category. Within each crop class, certain crops emerge as dominant. For instance, among herbaceous crops, alfalfa stands out as the most prevalent and representative, cultivated by 92% of the surveyed farmers across all *ksour* and oases. Similarly, among the 17 surveyed fruit tree crops, four crops dominate: date palm (grown by over 73% of farmers), olive tree (48%), fig tree (42%), and pomegranate (36%). The same pattern holds for pulses, with beans being the dominant crop (54%), and for vegetables, where turnips (45%), carrots (42%), and onions (38%) prevail. In the case of cereals, barley (55%) and corn (54%) dominate the cultivation practices.

The estimated richness of varieties is considerable, amounting to 183 varieties documented. However, this richness varies significantly across different oases, ranging from 104 varieties in the Tata Oasis to only 40 varieties in the Rich Oasis (Figure 3). Fruit trees contribute the most to varietal richness, accounting for 57% with 104 varieties, including 50 date palm varieties and 16 fig tree varieties.

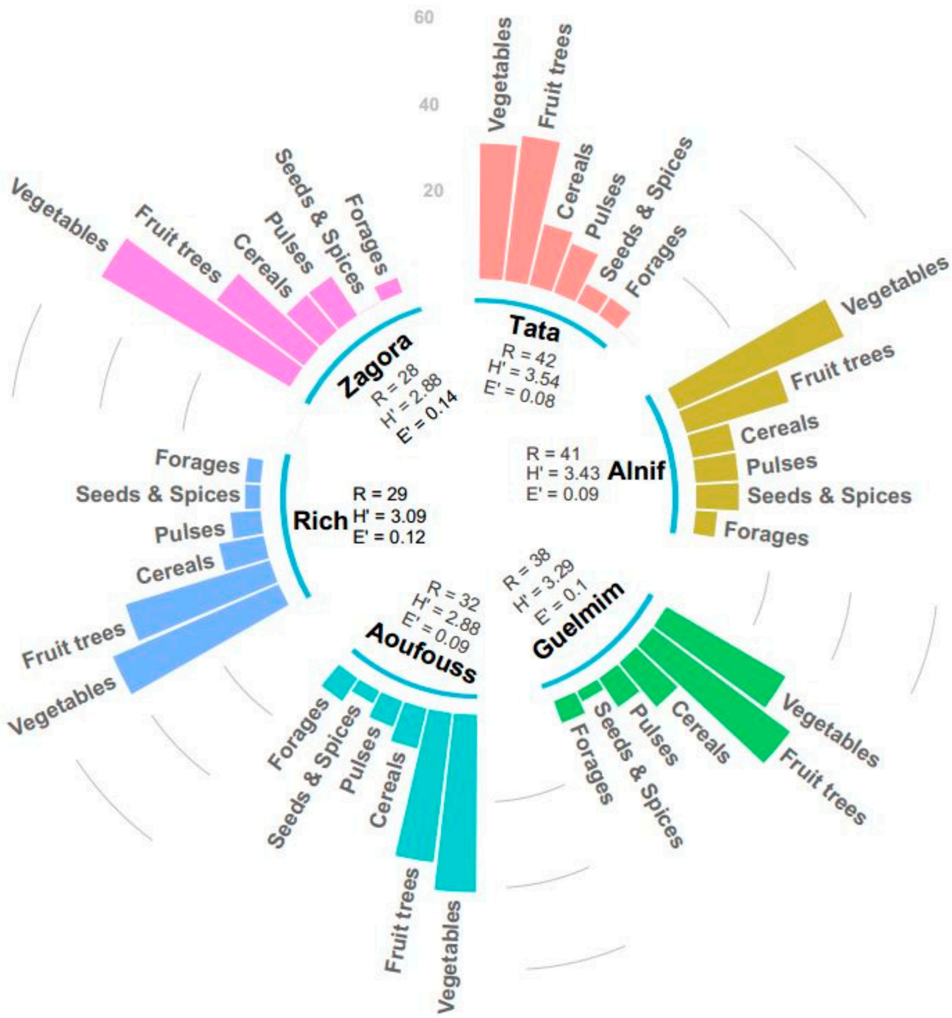

Figure 2. The different crops recorded in the oases studied (R: richness; H′: Shannon index; E′: equitability index).

Varietal richness is not consistent among the various crops grown. Notably, 31 crops lack named varieties, representing approximately 57% of the surveyed crops. This is particularly evident in vegetables, with 14 out of 20 crops lacking named varieties, as well as seeds and spices (5 crops), and pulses (3 crops).

The H′ values indicate a high level of diversity in varieties compared to crops, as all oases have values greater than 3. Specifically, H′ values range from 4.21 in the Tata Oasis to 3.34 in the Rich Oasis. However, the Piélou equitability index values are relatively low, ranging from 0.04 in the Tata Oasis to 0.11 in the Guelmim Oasis. These results align with the findings regarding crop diversity, highlighting the heterogeneous nature of the surveyed varieties.

Similar to crops, the surveys reveal the presence of dominant varieties that are widely cultivated, alongside rarer varieties limited to a few *ksour*. The latter are exclusive to specific oases and often recognized by only a small number of farmers. For instance, considering date palm varieties, the crop with the highest varietal richness, only two varieties are common across all five oases where date palms are grown (*Khelt/Sayer* and *Boufegouss*). Surveys in the Tata and Aoufouss oases identified 12 exclusive varieties, while the Zagora Oasis had 5 exclusive varieties, and Alnif and Guelmim had only 2 each. This pattern holds true for all crops, although with relatively lower proportions in terms of varietal richness for each crop. This aspect of varietal diversity highlights significant differentiation in the varietal profiles of the studied oases.

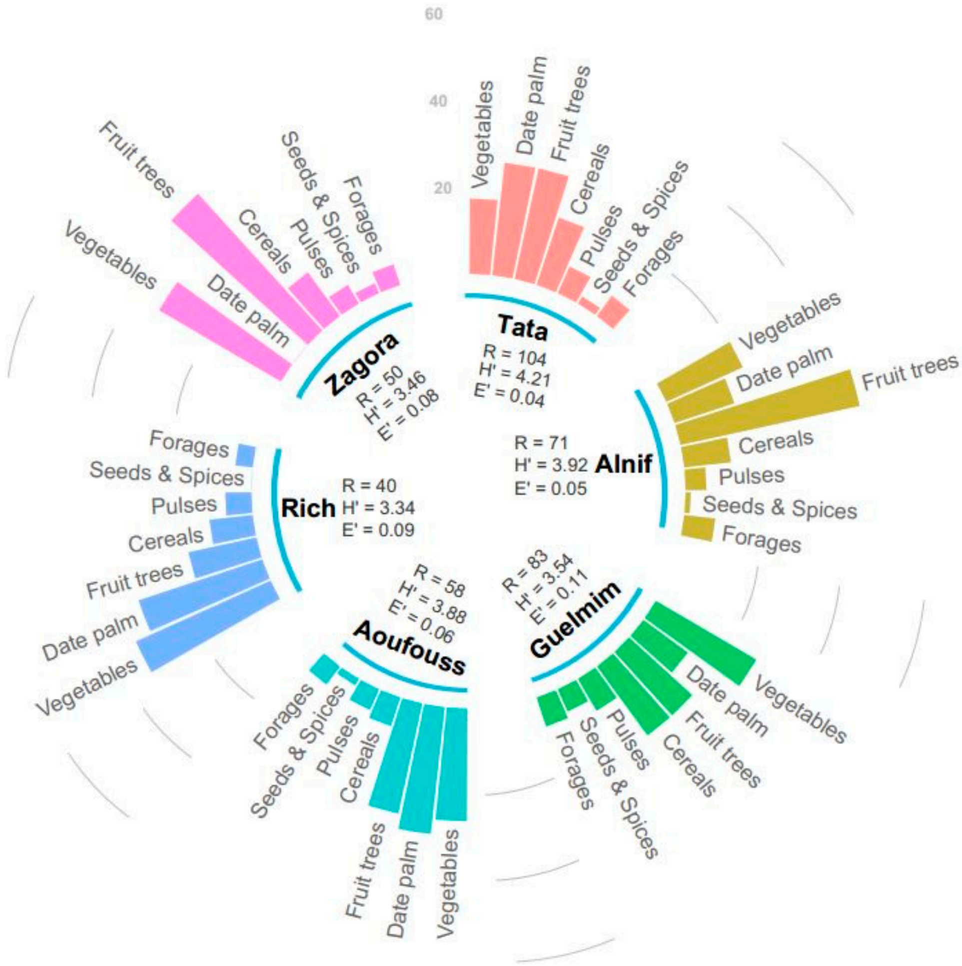

Figure 3. Varietal richness in the oases studied (R: richness; H′: Shannon index; E′: equitability index).

3.2. Typology of Farms and Diversity of Practices

The conducted surveys facilitated the collection of data regarding farm structure and agricultural practices in the *ksour* and oases under study. This enabled us to compare and characterize these oases, establishing a typology that aids in understanding the factors influencing agrodiversity variability. The sampling procedure involved collecting data from 600 farmers across 30 *ksar* and six oases.

In our survey, land tenure is exclusively direct, although farmers mention the existence of sharecropping known as *khamas* (sharecropper who cultivates land of which he is not the owner, in payment of one-fifth of its produce). Regarding land ownership, there is a diverse range of farm types, in addition to individual private property (*melk*), including traditional forms such as *habous* (status of land allocated by its owners to the ministry of Islamic affairs) or collective farms. Farmers may also acquire farms through lease or association. Generally, the *melk* type, and to a lesser extent the collective type, are the most prevalent in our sample. The Zagora oasis stands out with a relatively high prevalence of *habous* farms.

It is important to note that land ownership does not automatically entail ownership of palm trees and water shares for irrigation in the oases. These aspects of ownership are governed by customary laws that are still in practice. As for farm size, small farms dominate (Supplementary Material, Table S2). In fact, we can even refer to them as micro-farms, given that the average size of the cultivated plots is less than 1 ha and often smaller than 0.5 ha. Notably, the oases of Guelmim and Tata exhibit smaller plot sizes, averaging between 0.04 ha (400 m^2) and 0.17 ha (1700 m^2). The largest plots are found in the *ksour* of the Alnif oasis, with average plot areas ranging from 0.5 ha to 1.4 ha. On average, farmers have three to four plots, except for the oases of Guelmim and Tata, where the number is significantly higher. The total area of land operated by farmers is generally below 2 ha, varying from 1.4 ha to 1.7 ha, except for the oases of Guelmim and Tata, where the area ranges from 0.5 ha to 0.25 ha.

Regarding agricultural practices (Supplementary Material, Table S3), the conducted surveys revealed that the seeds used for the varieties are predominantly of local origin. Farmers either save seeds from the previous harvest or purchase them from local souks (markets). However, there is an observed increase in the use of selected seeds distributed by regional services of the Ministry of Agriculture or directly purchased by the farmers.

In terms of tilling, it is primarily carried out through traditional methods, often utilizing a sape or hoe, and less frequently using a plow. However, there is a clear trend towards mechanization, especially for cereal crops. Thus, a combination of traditional and modern methods coexists, with varying proportions depending on the oasis. The mechanized mode of land preparation is prominent in the Alnif oasis, where it is practiced by all farmers, and to a lesser extent in the oases of Zagora and Rich. On the other hand, the traditional mode predominates in the Tata and Guelmim oases. Hand weeding is practiced, and the biomass harvested during weeding serves as fodder for animals.

During the harvesting process, traditional methods are employed, such as using sickles for cereals and rakes for alfalfa. However, in terms of threshing, similar to tilling, there is a shift towards machinery usage. Fixed threshing machines are increasingly being used to replace the traditional method of threshing with animals.

One irrigation system, known as the basin system, is employed. However, variations exist among oases regarding the water source, which can be classified into three main types: *khettara* (underground gallery designed to convey water by gravity from the foothills of the mountains to the surface), *seguia* (an irrigation water channel), or pump wells. Pumping is increasingly utilized, often as an additional source. Diesel pumps are commonly used, although there has been a recent emergence of pumps running on butane gas. Generally, oases situated at the foothills of mountains rely on *khettara* for water supply, as seen in the cases of Alnif, Guelmim, and Tata. Oases that utilize water from the *seguia* are located along important river passages, such as Zagora and Aoufouss.

In terms of machinery usage for secondary agricultural tasks, such as crop transportation, worker movement, and equipment handling, tractors, trucks, or three-wheelers are increasingly employed. The traditional mode involves animal traction or animal-drawn carts. Different modes of transportation coexist in varying proportions across different oases and even within the practices of individual farmers.

The trend towards machinery usage aligns with what has been observed for tillage and threshing practices, with the oasis of Alnif being more mechanized compared to the dominant use of animal traction in the oases of Guelmim and Tata.

A principal component analysis was conducted to synthesize data on various aspects of all the *ksour* in the studied oases. This analysis considered variables such as farm size descriptors (total area, area per plot, number of plots), land nature, irrigation water supply, tillage, and machinery usage. The results reveal a distinct structuring of the studied oases (Figure 4, Supplementary Material, Table S4). The first two axes of the analysis account for 63.5% of the total inertia. Axis 1 explains 37.9% of the information, positively correlating with total farmed area, plot size, and machinery usage for tillage, mechanical threshing, transportation, and pump irrigation. The negative segment of axis 1 correlates more with variables indicating traditional practices in tillage, threshing, transportation, and fragmented property ownership. Axis 2 explains 25.6% of the total inertia and reflects the variability associated with land nature (predominantly *melk*) and the mode of water supply, contrasting the *khettara* type with the *seguia* type.

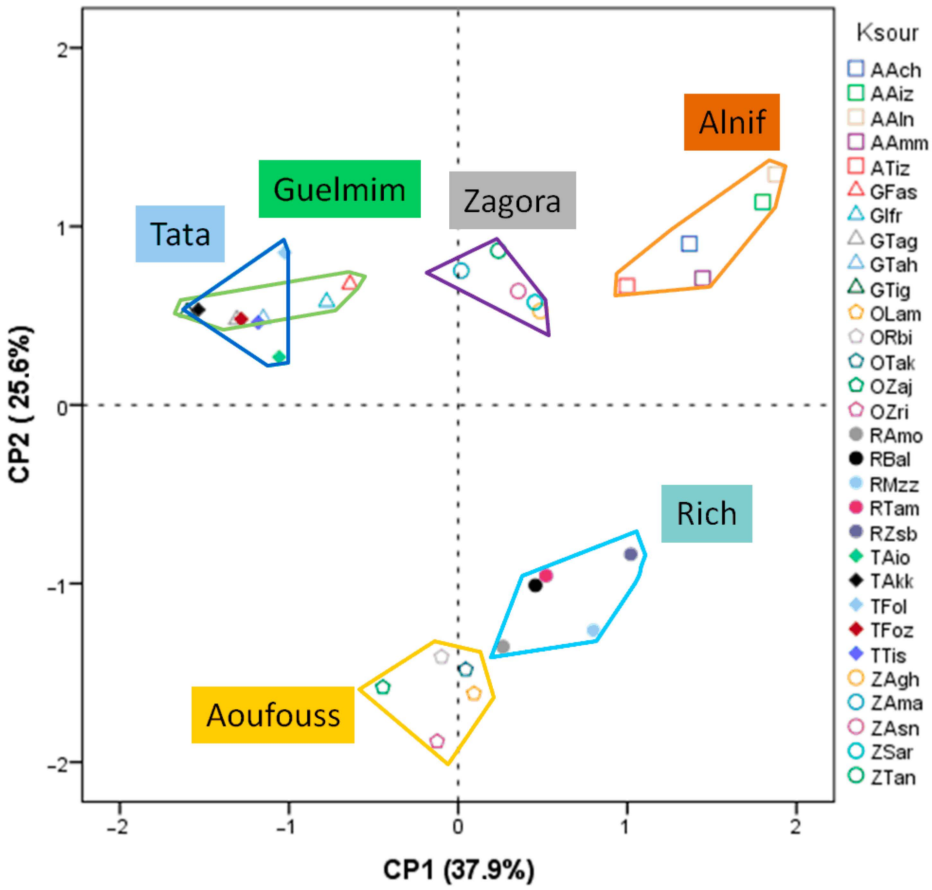

Figure 4. Typology of oases studied on the basis of agricultural practices projected in plans 1 and 2 of the Principal Component Analysis.

The observed structuring reveals the clustering of *ksour* within each oasis, with the exception of the *ksour* in the Tata and Guelmim oases. This finding is significant as it demonstrates the differentiation of oases based on farm structure and agricultural practices. Additionally, the observed structuring indicates a component of geographical proximity among the oases. Axis 1 represents a gradient of mechanization, with larger properties observed from the Tata and Guelmim oases to the Alnif and Zagora oases. The negative segment reflects traditional practices, while the positive segment represents modern practices. Axis 1 signifies a gradient of practice modernization through the introduction of machinery, which correlates with farm size and fragmentation. This gradient contrasts the Alnif oasis as an exemplar of modernized agriculture with the Tata and Guelmim oases, where practices are more traditional. For instance, in the Alnif oasis, machinery and farm size hold more importance, along with a water supply based on pumping. In contrast, the Tata Oasis is characterized by a lower level of machinery usage, a predominance of traditional practices, smaller farms, and a water supply system based on *khettara*. Axis 2 separates the Rich and Aoufouss oases primarily based on the mode of irrigation water supply via *seguia* and the relative significance of collective land ownership.

3.3. Varietal Profile of Oases

The results regarding crop and variety richness reveal a significant level of diversity and variability among the oases. The presence of specific crops and varieties suggests the potential differentiation of the oases into distinct variety groups, some of which may be more exclusive than others. Furthermore, the analysis of farm structure and agricultural practices has unveiled clear distinctions between the oases. This raises the question of the relationship between these two types of differentiation. To address this inquiry, we utilized the data obtained from the agrodiversity inventory, encompassing the 600 surveys conducted. Each oasis is described by 100 varietal profiles, corresponding to 20 farmers in five *ksour*, with each profile representing the list of crops cultivated by the interviewed farmer.

The collected data form a matrix of 600 observations (varietal profiles described by farmers) and 183 variables (varieties), which we subjected to factorial correspondence analysis (FCA). Given the large number of variables, the qualitative nature of the data, and the chosen analysis method, it was anticipated that the inertia expressed on the factorial axes would be dispersed. As a result, the first two factorial axes account for only 7.8% of the total inertia, distributed relatively evenly with 4% for axis 1 and 3.8% for axis 2. Initially, we can expect a lack of discernible structuring in the projection of the profiles on the factorial plane (1,2).

On the contrary, the obtained projection (Figure 5) reveals the opposite pattern, showcasing structured profiles despite the large number of observations (600 projected points). It is evident that the profiles of each oasis are distinctly grouped, forming well-defined and somewhat fragmented clusters. For instance, the profiles of the Tata and Zagora oases exhibit tighter clustering and less dispersion compared to Alnif or Rich, indicating a higher degree of profile homogeneity within these oases. The qualitative nature of the data used (presence–absence) explains the divergence from diversity indices that rely on quantitative data, where variety presence is weighted by frequency.

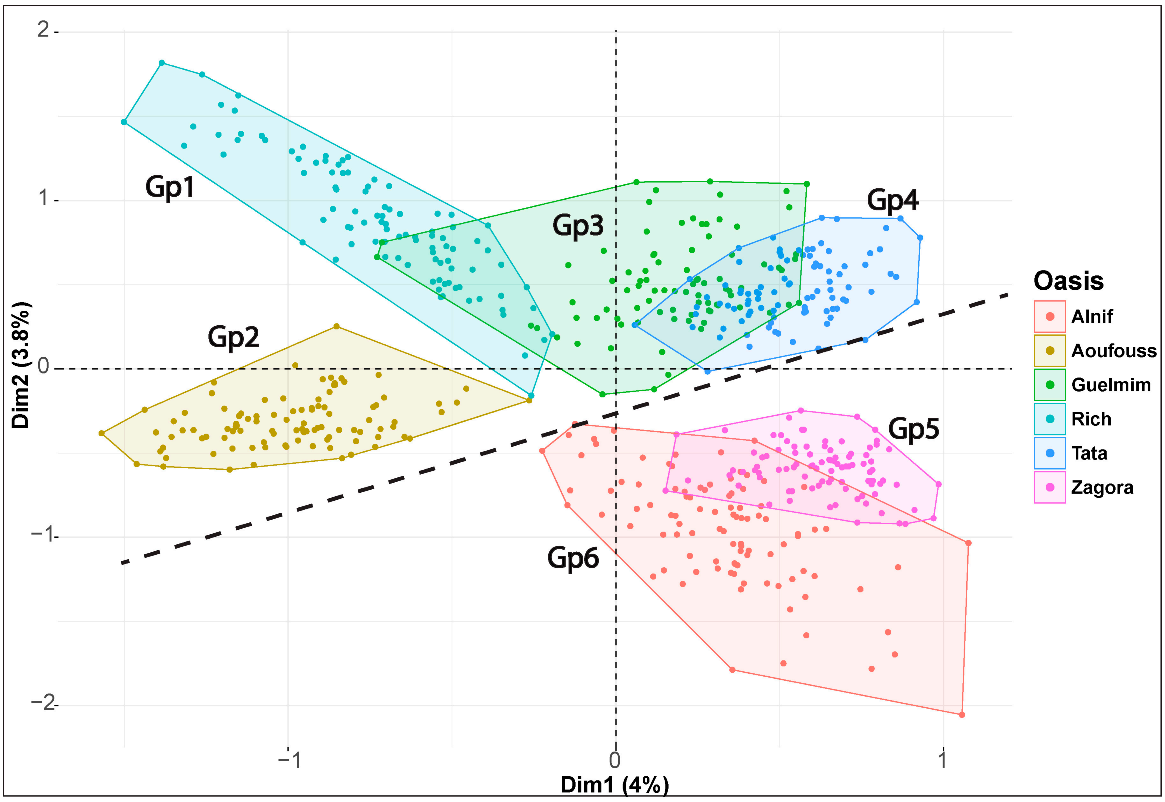

Figure 5. Projection of the farmers surveyed in planes 1 and 2 of the Factorial Correspondence Analysis.

Examining the projection allows us to identify two distinct groups. The first group comprises the Tata and Guelmim oases on the positive side of axis 1, and the Rich and Aoufouss oases on the negative side. The second group consists of the Alnif and Zagora oases on the negative side of axis 2. The first group represents a gradient that opposes the Tata and Aoufouss oases, with Guelmim and Rich occupying intermediate positions. Hence, a clear differentiation arises between the varietal profiles of the Tata Oasis and those of the Aoufouss Oasis. This indicates that the combinations of varieties used by farmers for different crops are similar within the same oasis, but differ from one oasis to another, elucidating the discrimination observed along the two axes of the analysis.

On the other hand, the proximity observed between the oases in the profile projection corresponds to their geographical proximity, as they are arranged in pairs of relatively close oases. This arrangement perfectly aligns with the differentiation highlighted by the typology of farms and agricultural practices. This finding is of utmost importance as it demonstrates the connection between practices and the structuring of agrodiversity. The projection of variables, i.e., the varieties that constitute the analyzed profiles in the factorial plane (1,2), allows us to highlight the varietal compositions that underlie the distinctions among the oases. This projection (Figure 6) reveals a structured pattern with six clusters of varieties, consisting of a central grouping (Gp3) and five lateral groupings (Gp1, Gp2, Gp4, Gp5, and Gp6) (Supplementary S1, Table S5). The central grouping (Gp3) encompasses common varieties, while the other groupings consist of varieties that differentiate between oases. It is important to note that the varieties within these groupings are not necessarily exclusive or specific to a particular oasis; they may be shared by two or more oases (Supplementary S1, Table S6). Thus, the Gp1 grouping enables us to identify the varieties that contribute the most to the differentiation of Rich's oasis, including a rare variety of durum wheat (*aghzzaf*), four apple tree varieties, as well as the presence of walnut, peach, and prickly pear (Supplementary Material, Table S7).

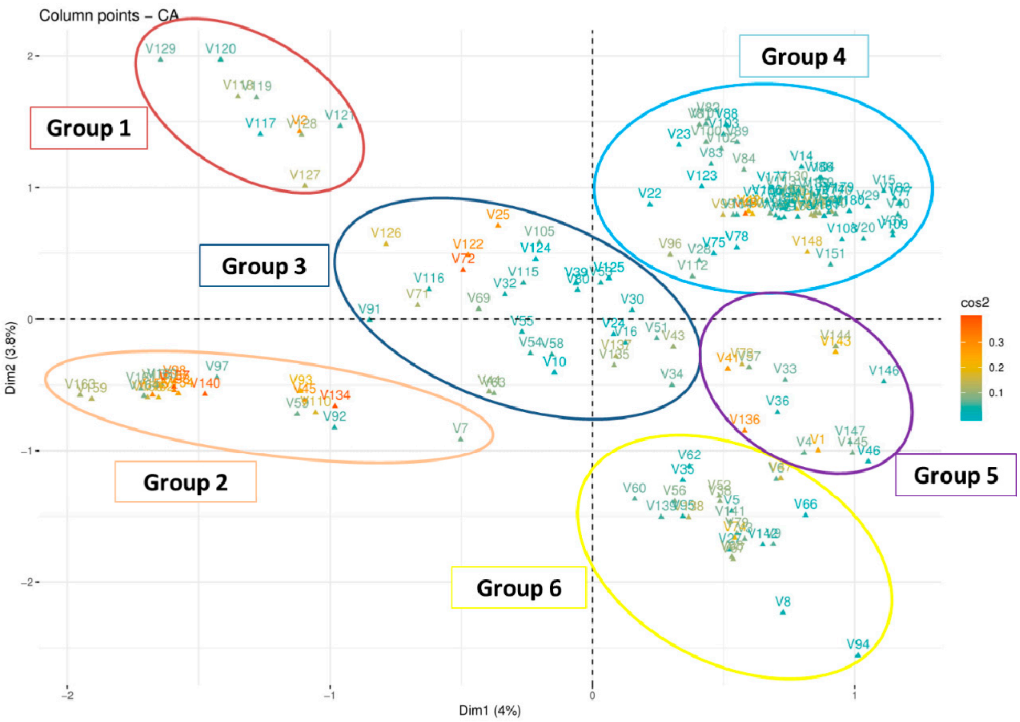

Figure 6. Projection of variables (183 varieties surveyed) in planes 1 and 2 of the Factorial Correspondence Analysis.

Gp2 primarily explains the distinction of the Aoufouss oasis through the presence of 12 varieties of date palm and two varieties of pomegranate (*Alânsri* and *Khrifi*) (Supplementary Material, Table S8). Gp4 consists of varieties that differentiate the oases of Guelmim (6 varieties of fig, 2 varieties of barley, etc.) and Tata (8 varieties of cereals, 4 varieties of fruit, 11 varieties of date palm), with some exclusive varieties and others that are common (Supplementary Material, Table S9). Gp5 represents a limited number of varieties that differentiate the Zagora oasis, with only three exclusive varieties (one okra variety and two date palm varieties), while the others are shared with one or two other oases (Supplementary Material, Table S10). Gp6 groups together the varieties that distinguish the Alnif oasis, consisting of cereals, vegetables, two varieties of fig tree, and three varieties of date palm (Supplementary Material, Table S11).

4. Discussion

4.1. Polyculture and Agrodiversity

The agrodiversity inventory revealed a significant level of crop richness, with a total of 55 crops cultivated. Previous studies conducted in the Aoufouss Oasis identified the presence of 23 crops [25]. However, the diversity of crops observed in this study is comparatively lower than that found in other traditional agroecosystems, such as the Rif Mountains, as reported by Ater and Hmimsa (2008) [65] and Hmimsa and Ater (2008) [66]. The variation in crop richness can be attributed to the more favorable climatic conditions and resource availability in the northern mountainous regions, in contrast to the challenging conditions in arid zones [52]. In comparison to other oases in North Africa, the southern Morocco region exhibits relatively higher crop richness. For instance, the Nafzaoua oases in Tunisia cultivate 27 crops [10], the Gafsa oasis in Tunisia cultivates 25 crops [9], the Chenini oasis in Tunisia cultivates 30 crops [75], the Oued Righ Oasis in Algeria cultivates 21 crops [11], Egypt cultivates 52 crops [57], and the Ghät Oasis in Libya cultivates 58 crops [54]. Hammer et al. [55] conducted an extensive inventory of crops across various Libyan oases, including Ghät, Fezzan, Ghadamès, Mourzouk, and Oubari, identifying a total of 278 crops. These findings highlight the significant role of these remote oases in the conservation of plant genetic resources.

Beyond quantifying the diversity and richness of crops, the oasis production system, based on polyculture, plays a vital role in ensuring local food security [58,65] and achieving partial or total self-sufficiency [52,76,77].

The diversity of crop classes, including cereals, pulses, fruit crops, and vegetables, provides a rich and balanced diet [78]. Our findings confirm the significance of vegetable crops, aligning with previous studies conducted in the oases of Errachidia and Ouarzazate provinces [42,79]. Notably, the relative importance of vegetable production compared to other herbaceous crops has emerged relatively recently, evident through the introduction of new crops in these oases such as watermelon, melon, beet, cucumber, lettuce, and potato [80].

This observed trend at the oasis level aligns with the broader pattern observed among smallholder farmers in southern countries, who increasingly prioritize horticultural cash crops while decreasing cereal cultivation [81,82]. Historical records mainly from travelers in the 18th and 19th centuries indicate that cereals were the primary herbaceous crop, while vegetable crops were neglected according to Follie (1792) [83], Adams (1810 and 1814), and Caille (1828) [84,85]. The small and limited size of farms necessitates trade-offs in crop proportions, suggesting that the development of new crops often comes at the expense of existing ones [86]. This observation underscores the fact that agrodiversity is intertwined with the choices made by local populations to meet their food needs [80].

The dynamics of agrodiversity in oases are closely linked to the socioeconomic dynamics of local peasant societies, including the choice between subsistence crops and cash crops, dietary preferences, and marketing channels. The cultivation of alfalfa exemplifies the impact of socioeconomic factors on crop selection in oases [86]. In the Aoufouss Oasis, Belarbi et al. (2004) [25] noted that the significance of alfalfa cultivation is relatively recent, dating back to the 1980s, even when farmers do not own livestock. Janati (1990) [87] reported that alfalfa occupies nearly 80% of the fodder areas in Moroccan oases and approximately one-third of the irrigated areas consistently throughout the year. Not only is it considered the primary fodder source, but it also generates significant added value [26]. Livestock plays a crucial role in oasis agroecosystems [10]. According to Sraïri et al. (2017) [26], alfalfa provides 34% of the total energy intake for livestock, whether in green or hay form, and occupies nearly 23% of the irrigated area in the Draa Valley. Locally produced dried alfalfa is highly sought after by farmers and animal nutrition professionals. Moreover, the dehydration process allows for year-round availability, facilitating transportation and storage.

4.2. Agrodiversity and Genetic Resources

Polyculture supports diversification and the conservation of genetic resources, as evidenced by our results. The richness and diversity of crops and varieties cultivated in oases contribute significantly to the conservation of genetic resources. In terms of different crops, we have observed the persistence of marginalized and increasingly neglected crops, such as spring cereals (barley, wheat), while millet and sorghum have been replaced by corn. However, there is substantial varietal diversity in cereals, particularly in specific oases like Tata, where 16 out of 29 cereal varieties were documented. According to Sraïri et al. (2017) [26], wheat and barley account for 38% and 13% of the cultivated area in the Draa Valley, respectively. Barley, in particular, is the most widely grown crop due to its resistance to water deficits [27].

At the horticultural level, we find the presence of rare crops with significant cultural heritage value, such as the cultivation of okra and cabbage varieties. Okra is a vegetable commonly grown in West Africa and has been cultivated since ancient times in Egypt and India [88]. The cabbage varieties grown in oases have an upright morphology distinct from the widely cultivated apple-type forms in Morocco, resembling ancient varieties found in northwest Spain and Portugal [89]. These unique crops contribute to the overall diversity and conservation of genetic resources in the oasis agroecosystems.

On the other hand, fruit tree cultivation, which is a key component of oasis agroecosystems, reveals significant richness in terms of crop and varietal diversity. We have identified 17 fruit species with a total of 54 varieties. The importance of fruit diversity has been acknowledged in traditional agroecosystems in the mountainous regions of northern Morocco [65,66]. Among these species, fig and olive trees are crucial elements in oasis agroecosystems, following palm trees [24]. The level of diversity within these species can vary significantly. For instance, there are 16 fig varieties, while the dominant variety for olive trees is the beldi variety, also known as "Picholine marocaine", with recently introduced selected varieties distributed by agricultural services. This finding aligns with the study conducted by Belarbi et al. (2004) [25] in the Aoufouss Oasis, which showed the dominance of the "Picholine marocaine" variety. Moreover, these results are consistent with the knowledge of genetic diversity for figs in traditional Moroccan agroecosystems [90], and the structuring of diversity in Moroccan olive groves [91].

The typology of oases with distinct geographical characteristics leads to the development of fruit crops adapted to their specific conditions, as seen in mountain oases. In the Rich Oasis, for example, there are six apple tree varieties, making it the most prevalent fruit crop in this oasis, along with the presence of walnut trees [53]. In 1984, the Ministry of Agriculture and Agrarian Reform launched the "walnut" operation as part of a project to enhance mountain fruit cultivation [42].

However, among fruit trees, the date palm stands out with the most extensive varietal profile, encompassing 50 varieties. This high richness surpasses the findings in Tunisian coastal oases, which host approximately 40 varieties [75,92], as well as the Siwa oasis in Egypt, where 52 varieties have been recorded [93]. However, it is important to note that this varietal richness is primarily dominated by khelt or hybrid varieties resulting from seedlings [25]. These varieties represent a significant reservoir of genetic diversity that contributes to the nourishment and enrichment of the existing diversity. Khelt, in this context, is a generic term that encompasses palms derived from spontaneous natural seedlings, typically hybrids of date palm varieties whose parentage is unknown. These khelt varieties account for over 55% of the total number of palms in Moroccan oases [94].

Within the same agroecosystem, there are additional species that reproduce through seedlings, such as the well-studied apricot tree [95,96] or the lesser-known pomegranate tree in the Tata oases. Therefore, we observe in fruit species the coexistence of spontaneous and cultivated forms. The distinction between domesticated and spontaneous forms is primarily determined by their respective modes of reproduction. Cultivated forms primarily rely on vegetative propagation, while spontaneous forms reproduce through random seed dispersal. The coexistence of these two forms creates a dynamic environment that promotes the conservation of genetic diversity by maintaining a connection between the spontaneous and cultivated compartments through gene flow.

4.3. Oasis Differentiation and Modernization of Practices

The geographic location of oases has a significant influence on their structuring and typology [17,18,96]. While the date palm is commonly regarded as the keystone species in oasis agroecosystems, there are highland oases where other fruit species, particularly those belonging to the rosaceous family, can take on the role of structuring species [70,86,97]. In our study, the Rich Oasis serves as an example, characterized by the absence of date palms due to the cold climatic conditions. Imilchil in the High Atlas region is a prominent oasis that exemplifies this type of agroecosystem in Morocco. It integrates the cultivation of vegetables, cereals, and fruits, along with livestock rearing through the practice of crop rotations [98]. This unique system was recognized as a Globally Important Agricultural Heritage System (GIAHS) by the FAO in 2011 [99].

In addition to altitude and its impact on climate, the water supply plays a direct role in determining oasis typology. Oases situated at the foothills of mountains rely on *khettara* systems for water supply (e.g., Alnif, Tata, Guelmim), while those located along river passages (e.g., Rich, Aoufouss, Zagora) depend on canal or *seguia* systems. The type of water supply influences the efficiency of water resource availability and the level of resource vulnerability [86]. In response to drought and increased water demand, particularly due to the growing cultivation of water-intensive crops like vegetables and fruits, farmers resort to pumping water from underground sources. Our typology synthesis results align with this interpretation. The availability and management of water resources are crucial factors in determining the vulnerability of oasis agroecosystems. Climatic hazards and the impact of human activities on the hydrological system, such as the construction of upstream dams, directly affect farming practices and crop choices. Oasis agroecosystems are fundamentally shaped by human intervention, characterized by the rational management of water and land [70]. Due to limited available land, farmers practice intensive agriculture, maximizing the use of their plots [100]. Consequently, farms in the six studied oases are characterized by micro-properties, with a farmer rarely cultivating an area exceeding one hectare. This observation aligns with the findings of Adriamainty fils et al. (2002) [53] in the oases of the Errachidia Province. Land tenure poses a constraint in oases as landholdings are often highly fragmented, with less than 1 hectare of total area in 95% of cases [101].

The conclusions drawn regarding the structure of farms confirm the trends highlighted in previous research. Ilahiane (2004) [102] states that oasis agriculture is characterized by small farms and scattered plots. The size of the cultivated plots is closely related to the availability of water resources [103]. However, it is important to note that this statement cannot be generalized, as the size of farms can vary. For example, the oases of Alnif and Zagora have relatively larger farms, with sizes of 1.68 hectares and 1.39 hectares, respectively. On the other hand, the oases of Tata and Guelmim show an opposite trend, with average farm sizes of 0.26 hectares and 0.53 hectares, respectively. Benaoun et al. (2014) [10] demonstrated that in the Nefzaoua oasis in Tunisia, 43% of plots have an area of less than 0.25 hectares, while only 15% have an area greater than 1 hectare. The structure of farms directly depends on the size of the oases, which is influenced by factors such as geomorphology (steep valleys, wide alluvial plains), and demographics. The fragmentation of farms into numerous and distant plots is also a direct consequence of inheritance practices. Therefore, the structure of farms results from a combination of natural constraints, which limit the availability of arable land, and socio-economic constraints, which lead to the fragmentation and dispersion of farms.

Tillage and agricultural practices play a significant role in differentiating oases and contribute significantly to their typological characteristics. The usage of machinery serves as an indicator of the level of modernization of practices, often at the expense of traditional methods. Our findings reveal a clear gradient in the modernization of practices, with the oases of Guelmim and Tata representing the traditional end of the spectrum, while Alnif serves as the modern pole. In the traditional pole, plowing and threshing are predominantly carried out using traditional methods, with tractors being rarely utilized. This is mainly due to the fragmentation and dispersion of plots, which pose challenges in terms of field access and the profitability of using machinery. Regarding water supply, while *khettara* systems are present in the oases of Alnif, Guelmim, and Tata, the prominent method in Alnif is irrigation through motor pumps from wells. In fact, 99% of farmers in Alnif rely on pumping from the water table to meet their water needs. A similar trend is observed in the oasis of Zagora, where farmers confirm the use of groundwater pumping for land irrigation. The introduction of groundwater pumping has led to a reduction in cereal crops in favor of water-intensive crops such as vegetables and alfalfa [25]. Surveys indicate that farmers often resort to purchasing water from other farmers who have wells equipped with motor pumps to compensate for the shortage in traditional water supplies, such as *khettara* and *seguia*, to sustain their agricultural practices and cultivate water-intensive crops.

4.4. Importance of Findings, Limitations and Directions for Future Research

Our results have revealed several negative consequences of modernization, including the erosion and loss of agrodiversity at both the species and variety levels, a potential shift from food crops to cash crops, and the increased vulnerability of agroecosystems due to excessive water consumption. While vegetable and legume crops are still maintained and practiced, certain local varieties of durum wheat, highly valued for their baking quality, have disappeared from these oases. It is crucial to encourage farmers to preserve local varieties in situ as these genetic resources are well-adapted to oasis conditions. Our findings provide valuable information for the conservation and sustainable use of all varieties cultivated in traditional oasis agroecosystems. These results are of great importance as they give us a general understanding of the current situation, which can help in formulating conservation strategies. Additionally, conducting the same study in the future would provide insights into the future of Moroccan oasis agriculture, including rare, disappeared, or introduced crops. National biodiversity conservation programs should support the maintenance of traditional varieties by oasis farmers. This approach not only addresses the impacts of climate change and desertification on oasis agroecosystems, but also creates employment opportunities for the younger generation, ensures the transmission of traditional agricultural knowledge, and enhances the sustainability of these traditional agroecosystems. By prioritizing local practices and knowledge over imported solutions from outside oasis communities, this approach offers a more integrated and locally rooted strategy.

The survey technique, based on semi-directed questionnaires, provides a wealth of information and a high level of precision, allowing us to deepen our understanding of the overall status of crop and variety diversity in Moroccan oasis agroecosystems. The adopted methodology has yielded significant results, revealing a remarkable diversity in both crops and varieties.

The analysis of farmers' discourse serves as a basis for characterizing norms and documenting a portion of the varietal diversity. However, relying solely on discourse does not provide a complete account of certain practices or enable us to inventory rare varieties. To comprehensively interpret how farmers perceive, think about, and manage agrodiversity, it was essential to understand the various social, economic, and environmental factors that directly or indirectly influence their choices. The discrepancies occasionally observed between discourse and practice were unintentional and often due to oversights. In general, more effective prospecting is achieved through in-depth investigations in specific areas. It is advisable not to rely on a single interview. Considering the sensitive nature of the research field, it is crucial to plan visits during favorable seasons. Typically, the initial visit should occur in winter when people have more time for discussions, establishing contacts, and collecting preserved materials such as seeds in sufficient quantities. The second visit can be scheduled during the summer months to observe and collect plants in their vegetative or mature stages (fruits and seeds). It becomes evident that the phases of maintenance, observation, and sampling need to be staggered according to the plant material and available opportunities. The presentation of plant samples, seeds, or fruits is highly valuable as it refreshes memories, confirms or refutes identifications, stimulates discussions, and occasionally opens up new possibilities for exploration.

5. Conclusions

Our study aims to characterize oasis agrodiversity using six representative oases in the southern region of Morocco. In particular, we selected the Rich Oasis as a mountain oasis to compare agroecosystems where the date palm is absent.

The study confirms that polyculture is the main characteristic of oasis agriculture. The richness and diversity of crops and varieties vary among the different oases. Each oasis has its unique varietal profile, highlighting the distinct choices and cultivation of crop varieties that contribute to their specific identities. It is essential to consider these variations in all planning efforts focused on the development and conservation of these agroecosystems. The agrodiversity we have highlighted represents a valuable plant genetic heritage that underpins local food security.

Identities within oases are also shaped by farm structure, land ownership, agricultural practices, and water supply. Our surveys have revealed that the modernization of agricultural practices is influenced by the structure of farms, including plot size, fragmentation, and dispersion. The modernization of irrigation techniques directly impacts water supply, with pumping from the water table partially or completely replacing traditional methods. While traditional methods have demonstrated their resilience over time and are essential for the rational management of water in oasis agroecosystems, the consequences of modernization for the integrity of oases and oasis agriculture are unfortunate and concerning.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13071413/s1: Table S1: Crops and varieties recorded in the oases studied; Table S2: Farm structure; Table S3: Agricultural practices; Table S4: Coordinates of the different variables studied (farming practices) in axes 1 and 2 of the Principal Component Analysis; Table S5: Coordinates of different varieties identified in planes 1 and 2 of the Factorial Correspondence Analysis; Table S6: The different varieties making up group 3 of the Factorial Analysis; Table S7: The different varieties making up group 1 of the Factorial Analysis; Table S8: The different varieties making up group 2 of the Factorial Analysis; Table S9: The different varieties making up group 4 of the Factorial Analysis; Table S10: The different varieties making up group 5 of the Factorial Analysis; Table S11: The different varieties making up group 6 of the Factorial Analysis; Supplementary S1: Survey conducted with farmers.

Author Contributions: Conceptualization, M.H., M.K. and M.A.; methodology, M.H., M.E.M., M.K. and M.A.; validation, M.K. and M.A.; formal analysis, M.H., J.K. and S.C.; software, M.H., J.K. and S.C.; investigation, M.H., M.E.M. and M.A.; resources, M.H. and M.E.M.; data curation, M.H., M.E.M. and M.A.; writing—original draft preparation, M.H., J.K., M.K. and M.A.; writing—review and editing, M.H., J.K., M.E.M., M.K., S.C., M.A. and A.-I.P.; visualization, M.H., J.K., M.K. and M.A.; supervision, M.K. and M.A., funding acquisition, A.-I.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the project *Smart and sustainable land use: solutions for resilient agriculture*, no. PN-III-P4-PCE-2021-1450, funded by the Romanian Executive Unit for Funding Higher Education, Research, Development and Innovation under the Romanian National Plan for Research—Development—Innovation 2014-2020, Program 2: *Increasing the competitiveness of Romanian economy through research, development and innovation*, Sub-program 2.1. *Competitiveness through research, development and innovation*, Category *Exploratory research project*.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to thank all the people who facilitated the surveys, as well as all the farmers who agreed to receive us and answer our questions. The authors would also like to thank the members of the Bio-Agrodiversity team for their fruitful discussions and comments. The authors would also like to thank Hafid Achtak, Ismail Souiri and Jamie Fico for their comments on earlier versions of this article.

Conflicts of Interest: We certify that there is no conflict in interest with any financial organization regarding the manuscript.

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