Intercropping in the Ouargla Oases under Saharan Conditions: Adoption, Diversity, and Vertical Stratification

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Abstract
This study examines the dynamics of intercropping adoption in the Ouargla oases, identifying the determiningfactorsthat influence this practice and itsrole in enhancing the resilience of agricultural systems to climate and socio-economic change. Between September 2021 and April 2024, a surveywasconductedamong 180 farms in three areas (Ouargla, N'goussa, and Sidi Khouiled), using a structured questionnaire. The results show that 75% of farmsadoptintercropping, but there are significantdisparities: N'goussa has the highest rate (82%), followed by Sidi Khouiled (74%) and Ouargla (67%). Adoption ischaracterised by systematic practices in N'goussa (64%), irregular practices in Ouargla (47%), and balanced practices in Sidi Khouiled. A comprehensiveinventoryidentified 57 intercroppedspeciesacross the studyregion, including 21 vegetablecrops, 8 foddercrops, 7 condimentcrops, 11 fruittrees, 6 aromatic and medicinal plants, 2 industrialcrops, and 2 cereals. Speciesdiversityvaried by zone, with N'goussaexhibiting the highestrichness (54 species), followed by Ouargla (50 species) and Sidi Khouiled (48 species). Speciesdiversitydynamicsremained stable between 2022 and 2024, with 57 speciesrecordedin 2022, increasing to 59 in 2023–2024. Correlationanalysisrevealedthat adoption resultedfrom an integrated set of technicalfactors (spacing, treeage), humanfactors (farmerage, education, motivation), organizationalfactors (extension contact, creditaccess, professionalmembership), and socio-psychologicalfactors (personalbeliefs, social influence). Plant stratification remains essential for ecologicalbalance:two-stratum systemsaccounted for 37% of farms in Ouargla, 45% in N'goussa, and 48% in Sidi Khouiled. An innovative two-stratum model combining fruit trees and vegetablecropswithout date palmsispresent on 10% of farms in N'goussa, showcasing local farmers' adaptability. The findings highlight thatintercroppingremains a valuablestrategy for oasis sustainability;itswidespread adoption requirestargeted public policies, including extension services, creditaccess, training for youngfarmers, and the promotion of local diversification initiatives.

Keywords: Intercropping, Determiningfactors, Oases, Vertical Stratification, Diversity, Ouargla

1.Introduction

The oases of southern Algeria, particularly in the Ouargla region, represent unique traditional agricultural systems shaped by centuries of adaptation to extreme desert conditions(Bouguedoura et al., 2015; Requier-Desjardins et al., 2024).In Sub-Saharan Africa, for instance, slash-and-burn and shifting cultivation systems have led to deforestation, soil degradation, and depletion, prompting the promotion of sedentary cropping systems with herbaceous legumes (Kim, 2025). Similarly, in the Xinjiang region of China, intercropping has been promoted to address ecological problems including increasing shortages of irrigation water and degradation of arable land, while aiming to diversify households' income generation sources (Dai et al., 2017; Shengwu & Juan, 2025). Intercropping plays a central role in these systems thanks to their vertical organization into three layers: date palms in the upper layer, shrubs in the middle layer and herbaceous crops in the lower layer (Benmoussa et al., 2022; Boucherit et al., 2024; El Janati et al., 2021). This architecture optimises the use of limited resources (water, light and soil), promotes biodiversity and improves soil fertility, while also diversifying agricultural production (Ariom et al., 2022; El Hafed et al., 2018; Rivest et al., 2025; Weih et al., 2022). Mixed cultivation has been advocated as an alternative to traditional farming systems, with the potential to increase the productivity of land and to diversify production (Patel et al., 2020). It is widely seen as a sustainable agricultural innovation, with enormous ecological, agronomic and economic potential, particularly in marginal regions with fragile ecosystems experiencing land degradation, water scarcity and unsustainable exploitation of natural resources (Dai et al., 2017). Globally, intercropping systems have been widely promoted as sustainable agricultural innovations (Mazzafera et al., 2021). In developing countries, governments often promote intercropping schemes to improve smallholders' income and address environmental degradation (Dai et al., 2017).The oases of Ouargla are home to over 2.5 million date palms, spanning almost 23,000 hectares, with 6,747.80 hectares dedicated to herbaceous crops (Ferrah & Oubelli, 2013),represent a critical case for understanding intercropping dynamics in marginal regions with fragile ecosystems.The introduction of modern technologies, land pressure, climate change, and the erosion of traditional practices are gradually altering plant architecture and farming methods. This threatens the productivity and sustainability of the system (Chaouch, 2018; CHAOUCH, n.d.; Salhi, 2020; Senoussi & Huguenin, 2021). Technical variables, including plant spacing, tree age, and water availability, also play decisive roles. In the Xinjiang case, (Dai et al., 2017)documented that intercropping created serious competition between crop and tree species for water, sunshine, and fertilizers, leading to dramatic declines in crop outputs (cotton production suffered a 30% decline, maize 55%, winter wheat 20%).Despite the importance of intercropping for oasis resilience, these systems are currently undergoing profound transformations. The introduction of modern technologies, land pressure, climate change, and the erosion of traditional practices are gradually altering plant architecture and farming methods, threatening productivity and sustainability(Chaouch, 2018; CHAOUCH, n.d.; Salhi, 2020; Senoussi & Huguenin, 2021). Similar challenges have been documented in other contexts, where inappropriate institutional environments and inefficient project management have hindered the successful implementation of intercropping programs (Dai et al., 2017; Maitra et al., 2021). In Xinjiang, for instance, despite government promotion of intercropping since late 2004, participants experienced significant losses in farming income, off-farm income, and gross income due to low and difficult-to-obtain subsidies, insecure land tenure, competition for resources, and the labor-intensive nature of intercropping (Dai et al., 2017).Studies on the adoption of intercropping practices, adaptation strategies and the factors influencing their sustainability remain limited, particularly in southern Algeria(Dib & Sardou, 2025). Given the central role of intercropping systems in the land use strategies and livelihoods of oasis farmers, it is surprising to find very little evidence of such studies being conducted within the context of the Algerian Sahara(Bouregaa, 2026). Assessing the impacts of intercropping programs on smallholders' incomes and identifying adoption determinants in poor regions facing ecological degradation is critically significant for policy development(Mohammed & Al-Amin, 2018).

This studyaims to addressthisgap by providing an integratedanalysis of currentintercroppingdynamics in the Ouargla oases, drawing on methodologicalapproachesfrom adoption studies in otherdeveloping country contexts, particularly the logisticregression and propensity score matchingapproachesemployed by (Kim, 2025)and(Dai et al., 2017), respectively. By identifying the factorsthatdetermine adoption includingtechnical variables, organizationalfactors, and socio-psychological dimensions, thisstudyseeks to provideevidence-basedrecommendations for supporting the transition toward more resilient and sustainable oasis agricultural systems.The study has four specific objectives: 1) assessing the level of intercropping adoption in the Ouargla oases; 2) conducting a speciesinventory and assessing plant diversitywithinintercroppingsystems; 3) analyzingintercroppingmodalitiesaccording to farm type (old versus new farms), withparticular attention to vertical stratification and its contribution to ecological balance and system sustainability; and 4) identifying the factorsinfluencingintercropping practices to informtargetedpolicy interventions.

2.Materials and Methods

2.1. Description of the study area

The Ouargla province is located in south-eastern Algeria and covers an area of 136.787 km², approximately 900 km from Algiers (MOHAMMEDI, 2023). As illustrated in Figure (1), the study area lies within the northern Sahara (Lower Sahara region), characterized by vast sand dunes and arid plains. The region experiences a hot desert climate (BWh), with summer temperatures often exceeding 45°C, an average annual temperature of 23.67°C, extremely low rainfall (~31.8 mm/year), and very high potential evaporation (254.4 mm/year) (Medjber Teguig et al., n.d.). This extreme aridity makes irrigation essential for all agricultural activities.Figure (1) shows that all three study areas are located within the Oued Mya basin, a depression that concentrates groundwater resources essential for oasis agriculture. The proximity of these three zones (5 to 25 km apart) allows for comparative analysis while controlling for macro-climatic variations. The spatial distribution of study sites enables investigation of how local factors (distance from urban centers, access to infrastructure, land tenure history, and agricultural development policies) influence intercropping adoption independently of regional climatic constraints.

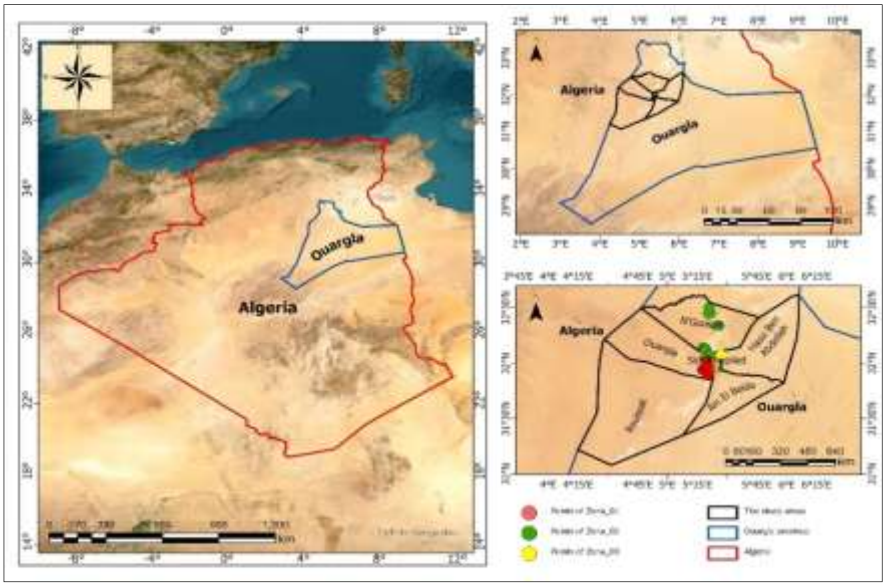

Figure 1. Location of the study area (Algerian government through subsidy programs (CDARS, 2024)).

2.2. Conceptual framework for adoption analysis

Understanding the adoption of intercropping in oasis systems requires a comprehensive conceptual framework that integrates multiple dimensions of farmer decision-making.Drawing on adoption theories from agricultural innovation literature (Bahnasy, 2025; Stempfle et al., 2025)and empirical findings from arid and semi-arid regions(Dai et al., 2017; Kim, 2025), we propose an integrated framework that conceptualizes intercropping adoption as a function of five interacting dimensions: (1) technical and biophysical factors, (2) human capital and demographic characteristics, (3) organizational and institutional factors, (4) socio-psychological dimensions, and (5) economic factors.

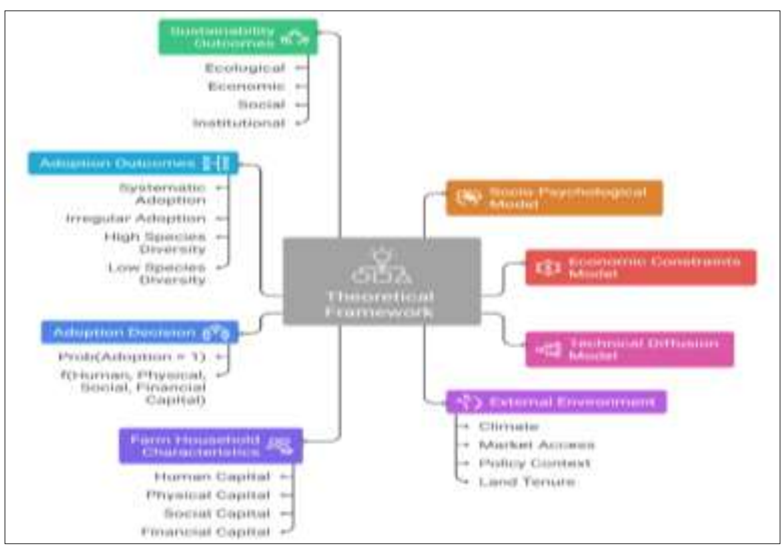

Figure 2. Conceptual framework of intercropping adoption determinants in oasis systems.

The conceptual framework posits that intercropping adoption is a function of farm household characteristics embedded within an external environment. Adoption outcomes manifest as varying degrees of systematicity (regular vs. irregular) and species diversity (low, medium, high), which ultimately determine sustainability outcomes across ecological, economic, social, and institutional dimensions.

2.2.1. Theoretical foundations of adoption

49 farms practiced intercropping, with diversity distributed as 8 low, 28 medium, 13 high, and adoption predominantly systematic (38 systematic, 11 irregular). In Zone 03 (Sidi Khouiled), 45 farms practiced intercropping, with diversity distributed as 7 low, 25 medium, 11 high, and 2 "reliable" (a local category indicating medium-high diversity), with adoption relatively balanced (24 systematic, 21 irregular).

Table 1. Distribution of the sample according to the areas surveyed.

Area	Municipalities concerned	Totalfarms	Sample	Old farms	New farms
Area01 (Ouargla)	Ouargla, Rouissat	**5641**	**60**	**42**	**18**
Area 02 (N'goussa)	N'goussa	**1873**	**60**	**39**	**21**
Area 03 (Sidi Khuiled)	Aïn Beida, Hassi Ben Abdellah, Sidi Khuiled	**5365**	**60**	**12**	**48**
Total		**12879**	**180**	**93**	**87**

2.3. Species inventory and diversity assessment

A complete inventory of intercropped species was conducted over three growing seasons (2021/2022, 2022/2023, 2023/2024). For each species, the number of farmers cultivating it as an intercrop was recorded, Species were classified into seven crop classes: fodder crops (CIF), vegetable crops (CIM), condiment crops (CICON), aromatic and medicinal plants (PM/AR), industrial crops (CI IN), cereals (CICe), and fruit trees (ARFRUI). Diversity was categorized as low (less than 6 species per farm), medium (6-12 species), or high (more than 12 species).

2.4. Statistical data analysis

Statistical analysis was performed using IBM SPSS Statistics software, version 23.A combination of methods was used for this analysis:

- Descriptive statistics: tosummarise and describe the data (frequencies, means, percentages, and standard deviations).
- Inferential tests: To draw conclusions beyond the sample, including: Student's t-test, Chi-square test (x^2), Cramer's V coefficient. A significance threshold of $p \leq 0.05$ was set to determine the validity of the statistical results.

The statistical analysis proceeded in three stages:

Stage 1: Descriptive analysis of intercropping adoption rates, species diversity, and stratification patterns across zones.

Stage 2: Bivariate analysis using chi-square tests of independence to examine associations between adoption and individual factors (farmer age, palm age, water availability, spacing). Cramer's V coefficient was used to measure association strength:

$$\mathbf{V} = \sqrt{\frac{\mathbf{X^2}}{\mathbf{n \times \min(r-1, c-1)}}}$$

where $\chi 2$ is the chi-square statistic, n is the sample size, and r and c are the number of rows and columns in the contingency table. Interpretation of V follows: V < 0.1 = very weak, 0.1-0.3 = weak, 0.3-0.5 = moderate, > 0.5 = strong.

Stage 3: Multivariate analysis using logistic regression to identify the independent determinants of systematic adoption. The logistic model is specified as:

$$\ln\left(\frac{\mathbf{P(systematic\ adoption)}}{\mathbf{1 - P(systematic\ adoption)}}\right) = \alpha + \sum_{k=1}^{K} \beta_k X_{ik}$$

where X_{ik} represents the k^{th} independent variable for farmer i. Marginal effects are calculated as:

$$\frac{\partial \mathbf{P}}{\partial \mathbf{X_k}} = \beta_k \times \mathbf{P(1-P)}$$

3.Results

3.1. Intercropping presence and adoption degree

Figure 2 shows that 75% of farms (135 out of 180) practice intercropping. The practice of intercropping varies significantly between the three study areas. N'goussa has the highest rate (82%), compared to 76% in Sidi Khouiled and 67% in Ouargla (Figure 03). These differences are confirmed by statistical analysis using dispersion indicators. In N'goussa, the mean is relatively low and the standard deviation is small (1.08 ± 0.270). By contrast, the values observed in Ouargla (1.29 ± 0.457) and Sidi Khouiled (1.25 ± 0.452) are higher. In N'goussa, regular adoption (systematic practice across the entire plot) is high 64%. Conversely, the Ouargla zone is characterised by rather irregular adoption, applied partially or seasonally (47%). Sidi Khouiled occupies an intermediate position, characterised by a balance between the two forms of adoption, with a difference of around 5% (Figure 4).

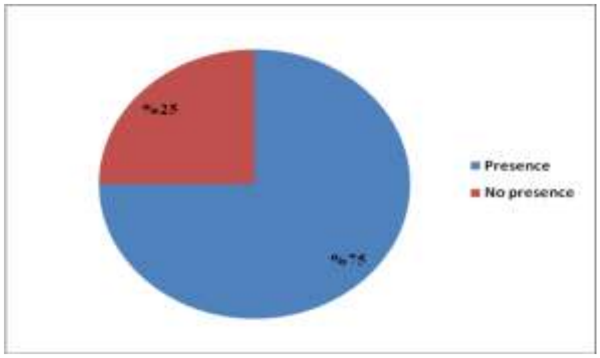

Figure 2. Proportion of farms practising intercropping in the study region (n = 180).

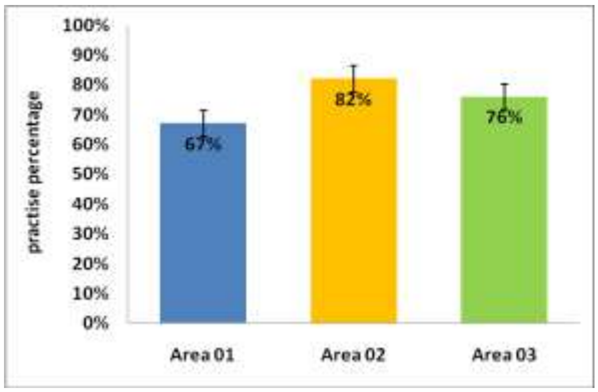

Figure 3. The percentage of farms practising intercropping in each area (Area 1: Ouargla; Area 2: N'goussa; Area 3: Sidi Khouiled).

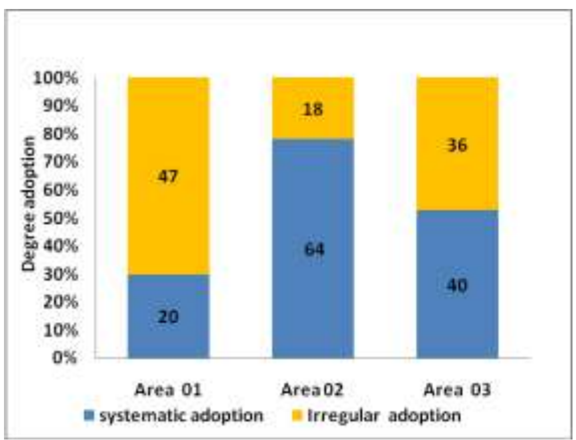

Figure 4. Distribution of farms according to the degree of adoption intercropping (systematicand irregular) by area (Area 1: Ouargla; Area 2: N'goussa; Area 3: Sidi Khouiled).

3.2. The practice and type of farming (Old and new farms)

The analysis reveals marked spatial variability in this practice, linked to the type of farm. Old farms predominantly practise intercropping in Ouargla (30 farms) and N'goussa (37 farms), while new farms predominantly practise intercropping in Sidi Khouiled (36 farms) (Figure 05). Based on the statistical results of the T-test, a significant difference was observed only in N'goussa ($t = 2.6$; $p = 0.00$). However, no statistically significant differences were observed in the Ouargla ($p = 0.075$) or Sidi Khouiled ($p > 0.05$) areas.

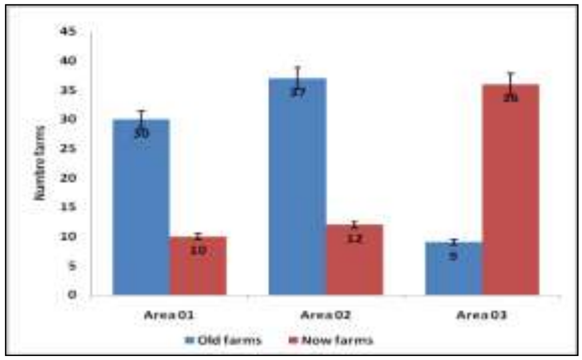

Figure 5. Number of farms practising intercropping, categorised by farm type (old and new farms).

3.3. Species diversity

Table 2 presents the inventory of intercroppedspeciesrecorded in the Ouargla oases, comprising57 speciesbelonging to 27 botanicalfamilies. This level of speciesrichness highlights the high diversitymaintainedwithin oasis intercroppingsystems. The recordedspeciesweredistributedamongseveral major crop groups, includingvegetables, foddercrops, aromatic and condiment plants, fruit trees, cereals, and industrial or othercrops. Vegetablesrepresented the largest component of the inventory, reflectingtheir central role in householdconsumption and local markets, whilefoddercrops, particularlyalfalfa, illustrated the close integrationbetweencrop production and livestockhusbandry. The floristic composition alsoshowed a considerablediversity of aromatic, condiment, and medicinalspecies, includingcoriander, parsley, mint, basil, thyme, rosemary, and otherspeciestraditionallycultivated in oasis systems. Fruit treesconstitutedanother important component, withpomegranate, apricot, fig, citrus, grapevine, peach, olive, and pearamong the speciesrecorded. The presence of cereals and industrialcrops, althoughless diverse, furtherillustrates the multifunctionality of intercropping practices in the study area.

The diversityobserved in Ouargla is comparable with, and in some respects exceeds, thatreported for other North African oasis systems. Aljane et al. (2020) documented 32 fruit species in Tunisianoases, whereas Houssni et al. (2020) reportedapproximately 45 cultivatedspecies in Moroccanoases. The relatively high richnessobserved in Ouargla mayberelated to the long agricultural history of the oasis, the coexistence of traditional and modern production practices, and farmers' continued use of diverse speciesadapted to local environmental and socioeconomic conditions. Overall, the inventorydemonstratesthatintercropping in the Ouargla oasesis not limited to a smallnumber of dominant crops but constitutes a diversified production strategycombiningfood, fodder, commercial, aromatic, medicinal, and ecologicalfunctions. This speciesdiversityprovides an important basis for assessing the typology and dynamics of intercroppingsystems in the subsequent sections.

Table 2. Diversity of intercropped species recorded in Ouargla oases in 2021/2022

Crop group	Number of species	Main species recorded
Vegetables	21	Tomato, red beet, purslane, spinach, onion, garlic, turnip, radish, carrot, lettuce, eggplant, pumpkin, bottle gourd, okra, melon, watermelon, local melon, potato, asparagus, broad bean, bell pepper, cabbage
Fodder crops	8	Alfalfa, fodder barley, fodder cabbage, sorghum, maize, millet, sunflower, panicum
Condiments and aromatic plants	13	Coriander, green anise, celery, safflower, parsley, mint, basil, fennel, thyme, rosemary, Saffron, laurel, fenugreek
Fruit trees	11	Pomegranate, apricot, plum, fig, orange, lemon, quince, grapevine, peach, olive, pear
Industrial and cereal crops	4	durum wheat, oat, cotton, henna,
Total	57	

3.3.1. Species dynamics

Table 3 shows that total intercropped species increased from 57 in 2022 to 59 in 2023, with no net change between 2023 and 2024. Two new species (sunflower, panicum) were introduced in 2023, and no species disappeared during the study period. The rate of change was +3.51% between 2022 and 2023, stabilizing at 0% thereafter.

The absence of species disappearance is a positive indicator of system resilience. In many agricultural systems undergoing modernization, species loss (genetic erosion) is common (Khoury et al., 2022). The fact that no species were lost over three years suggests that farmers maintain even minor species for cultural, medicinal, or risk management purposes. This aligns with the concept of "agrobiodiversity as insurance" (Sidibé et al., 2018), were diverse portfolios buffer against environmental shocks and price volatility.

The addition of sunflower and panicum in 2023 indicates that the intercropping system evolves in response to new opportunities. Sunflower was likely introduced following government promotion of oilseed crops to reduce dependence on imported vegetable oils (Algeria imports approximately 70% of its edible oils). This stability in Ouargla contrasts with other North African oases. (Benmoussa et al., 2022) reported a decline in traditional fruit tree varieties in Tunisian oases as farmers shifted toward date palm monoculture, while (Houssni et al., 2020) documented loss of cereal and legume varieties in Moroccan oases due to groundwater depletion. However, three years of data provide valuable trend information, longer time series (10-20 years) would be needed to distinguish cyclical variation from long-term trends.

Table 3. Evolution of the number of species and diversity dynamics (n=180 farmers).

Evolution of the number of species and diversity dynamics in the associated cropping system (n = 180 farmers)						
Year	**Total number of species recorded**	**New species**	**Disappeared species**	**Net change**	**Rate of change (%)**	**Share of global total (%)**
2022	57	—	—	—	—	0.9661
2023	59	2	0	2	0.0351	1
2024	59	0	0	0	0	1

3.3.3. Distribution by crop class and zone

Table 4 shows the distribution of intercropped species among the different crop classes across the three study zones. Overall, 57 species were recorded in the study area. Species richness varied among zones, with 54 species recorded in N'goussa, 50 in Ouargla, and 48 in Sidi Khouiled, indicating a relatively high level of species diversity throughout the study area. These figures refer to the number of species recorded within each zone and may include species occurring in more than one zone.

Foddercrops and vegetablecropswereamong the mostrepresented groups, with 8 and 21 species, respectively, in the overallinventory. Fruit treesconstitutedanother important component, with 11 species, followed by condiment plants (7 species) and aromatic and medicinal plants (6 species). Industrialcrops and cerealcropswerelessrepresented, withtwospecieseach. This composition illustrates the multifunctionalcharacter of oasis intercropping, combiningfood, fodder, commercial, aromatic, medicinal, and perennialcrops.

Vegetablecropswereconsistentlywellrepresentedacross the three zones, with21 species in Ouargla, 21 in N'goussa, and 22 in Sidi Khouiled. Foddercropsincluded7 species in Ouargla and N'goussa and 6 in Sidi Khouiled. Condiment plants wererepresented by 5 species in Ouargla, 7 in N'goussa, and 8 in Sidi Khouiled, whilearomatic and medicinal plants accounted for 5, 5, and 4 species, respectively.

Fruit-treediversitywashighest in N'goussa (11 species), comparedwith9 species in Ouargla and 8 in Sidi Khouiled. This relatively high representation of perennialspeciescontributes to the structural and functionaldiversity of the oasis agroecosystem. Industrialcropswererecorded in Ouargla and N'goussa, with1 and 2 species, respectively, but were absent from Sidi Khouiled. Cerealcropswererepresented by 2 species in Ouargla, 1 in N'goussa, and none in Sidi Khouiled.

The Shannon diversity index for the entirestudy area wasH′ = 3.89, while the evenness index wasJ′ = 0.95. These values indicate a high level of speciesdiversity and a relativelyequitable distribution of species. Overall, the results highlight the diversified and multifunctional nature of intercroppingsystems in the Ouargla oases, whilealsorevealingdifferences in crop-class composition among the three zones.

Table 4. Distribution of the number of species by crop class and zone.

Distribution of the number of species by crop class and zone (Zone 1, 2, and 3)								
Zone	**Intercropping Groups**							**Total species**
	CIF	**CIM**	**CICON**	**PM/AR**	**CIIN**	**CICe**	**ARFRUI**	
Zone 01 (Ouargla)	7	21	5	5	1	2	9	50
Zone 02 (N'goussa)	7	21	7	5	2	1	11	54
Zone 03 (Sidi Khouiled)	6	22	8	4	0	0	8	48
Total	**8**	**21**	**7**	**6**	**2**	**2**	**11**	**57**

The Shannon diversity index (H′) for the entire study region is 3.89, with evenness (J′) of 0.95, indicating high and equitable distribution of species across the 57 categories.

3.3.4. Species diversity by farm

Table 5. Distribution of species diversity by zone (number of farms).

Diversity level	Zone 01 (Ouargla)	Zone 02 (N'goussa)	Zone 03 (Sidi Khouiled)	Total
Low (<6 species)	13	8	7	28
Medium (6-12 species)	23	28	28	79
High (>12 species)	4	13	11	28
Total farms practicing CI	**40**	**49**	**45**	**135**

Table 5 shows the distribution of speciesdiversityamong the 135farmspracticingintercropping, representing 75% of the total sample. Overall, farmswithmedium speciesdiversity (6–12 species)were the mostcommon, accounting for 79 farms (59.0%), whilelow- and high-diversityfarmseachrepresented28 farms (20.9%). This distribution indicatesthatintercropping in the Ouargla oasesisgenerallycharacterized by a moderatelevel of speciesdiversity, althoughsubstantialdifferencesexistamong the threestudy zones.

In Zone 01 (Ouargla), medium-diversityfarmswerepredominant (23 farms;57.5%), followed by low-diversityfarms (13;32.5%), whereasonly 4 farms (10.0%) exhibited high speciesdiversity. This relativelylowrepresentation of highlydiversifiedfarmsmayreflect the combinedeffects of urban expansion, land fragmentation, ageing of traditionalfarms, and environmentalconstraintsaffecting agricultural production.

In Zone 02 (N'goussa), medium-diversityfarmswerealso the largest group (28;57.1%), followed by high-diversityfarms (13;26.5%) and low-diversityfarms (8;16.3%). The relatively high proportion of highlydiversifiedfarmssuggests the persistence of diversifiedintercropping practices in this zone, wheretraditional oasis production systemsremaincomparativelywellrepresented.

Zone 03 (Sidi Khouiled)showed a similarpredominance of medium-diversityfarms, with28 farms (62.2%), while 11 farms (24.4%) had high diversity and 7 (15.6%) hadlowdiversity. The relativelysubstantial proportion of highlydiversifiedfarmsindicatesthatintercropping in this zone is not limited to simplified commercial production, but alsoincludesfarmsmaintaining a broad range of cultivatedspecies.

The spatial distribution thereforereveals a predominance of medium speciesdiversityacross all three zones, while the proportion of low-diversityfarmswashighest in Ouargla and that of high-diversityfarmswashighest in N'goussa. Thesedifferences are consistent with the contrastingcharacteristics of the oasis systems, particularly in terms of farmhistory, land-use dynamics, production orientation, and access to agricultural resources.

However, speciesrichnessbasedsolely on the number of cultivatedspeciesshouldbeinterpretedwith caution. The number of speciesdoes not necessarilyreflecttheirfunctional contribution to the agroecosystem. For example, a farmcultivating 13 vegetablespeciesmay have lowerfunctionaldiversitythan a farmcultivatingeightspeciesbelonging to complementaryfunctional groups, such as vegetables, legumes, foddercrops, aromatic plants, and fruit trees. Consequently, future analyses could complement species richness with functional diversity indicators that conside recological and agronomic complementarity among species.

3.4. Factors influencing intercropping adoption

3.4.3. Bivariate analysis: chi-square and Cramer's V

This analysis aims to assess the influence of certain key factors on the practice of intercropping in the studied areas. The analysis is based on the chi-square independence test, supplemented by Cramer's V coefficient to measure the strength of the observed associations (Table6).

Table 6. The chi-square independence test of factors influencing the adoption of intercropping (Area 01: Ouargla; Area 02: N'goussa; Area 03: Sidi Khuiled).

Indicator	**Area**	**Khi-square**	**p-value**	**Cramer's V**	**Interpretation**
Farmer age	Area01	7.83	0.02	0.20	**Significant and weak.**
	Area02	6.93	0.04	0.39	**Significant and moderate.**
	Area03	11.46	0.000	0.42	**Significant and moderate to strong.**
Age of the palm tree	Area01	15.73	0.001	0.24	**Significant and weak.**
	Area02	18.86	0.00	0.45	**Significant and moderate.**
	Area03	8.13	0.04	0.55	**Significant and very weak.**
Water availability	Area01	0.56	**0.33**	**0.07**	**No significant and very weak.**
	Area02	4.42	0.035	0.27	**Significant and weak to moderate.**

	Area03	4.03	0.045	0.26	**Significant and weak to moderate.**
Spacing	Area01	13.98	0.007	0.22	**Significant and weak.**
	Area02	18.83	0.000	0.54	**Significant and strong.**
	Area03	**24.80**	**0.000**	**0.62**	**Significant and very strong.**

The chi-square test results reveal significant relationships between intercropping adoption and three key variables farmer age, palm tree age, and spacing across all studied zones ($p < 0.05$). Water availability shows significance only in N'goussa and Sidi Khouiled, remaining insignificant in Ouargla ($p = 0.56$).

Cramer's V coefficients assess association strength. In Ouargla, all associations were weak (V = 0.19-0.24), reflecting the zone's irregular adoption patterns. In N'goussa, spacing showed a strong association (V = 0.54), while palm age and farmer age showed moderate associations. In Sidi Khouiled, strong associations were observed for spacing (V = 0.62) and palm age (V = 0.55), with farmer age showing moderate-to-strong association (V = 0.42).

Water availability analysis shows a very weak association in Ouargla (V = 0.07), consistent with the zone's water quality problems where salinity rather than availability limits adoption (Laradj, 2017). The weak association in Ouargla suggests that even when water is available, other constraints (land fragmentation, farmer age) limit intercropping. In contrast, N'goussa and Sidi Khouiled show weak-to-moderate associations (V = 0.27), indicating water availability remains a meaningful factor in those zones. These findings highlight that spacing and palm age are the most consistent predictors of intercropping adoption across all zones.

3.4.4. Socio-psychological dimensions and the adoption of intercropping

Table 3 shows the results of the socio-psychological dimension analysis, revealing significant disparities between the three study areas. Personal beliefs and convictions towards intercropping appear to be the most influential socio-psychological factor, with an average of 45% of farmers expressing positive views (peaking at 55% in the N'goussa area). Social influence is also strong there 70%, whereas it remains low in Ouargla 10%. On average, 43% of farmers are membership in the of professional organisations, peaking at 63% in N'goussa. Most farmers have a primary and middle school 41%, only 13% have an academic. Degree and access to agricultural education is limited (19%, slightly higher in Sidi Khouiled at 25%). Finally, personal motivation is high among around half of the farmers, reaching 70% in N'goussa and 60% in Zone 3, compared to just 20% in Ouargla.

Table7. Socio-psychological dimensions and adoption of intercropping (%).

Socio-psychological dimensions	Modalities	Percentage %			
		Area 01	Area 02	Area 03	Average
Personalbeliefsand convictions	Positive	**40**	**55**	40	45
	Neutral	20	10	20	17
	Negative	**40**	35	**45**	**47**
Social and collective effect	Strong	10	**70**	**40**	**40**
	Medium	25	20	25	23
	Low	**65**	10	35	37
Membership in the professional organization	Yes	42	**63**	24	43
	No	**58**	37	**76**	**57**
Education levels	Illiterate	22	18	25	22
	Primary and middle school	**38**	**45**	**41**	**41**
	Secondary	28	28	17	24
	Academic	12	9	17	13
Agricultural education	No	80	67	75	74
	Yes	10	**23**	**25**	19
Personal motivation	Strong	20	**70**	**60**	**50**
	Medium	30	20	30	27
	Low	**50**	10	10	23

3.5. Logistic regression results for systematic adoption

Table 8 presents logistic regression results identifying the strongest predictors of systematic intercropping adoption. The model correctly predicts 81.2% of adoption outcomes, with Nagelkerke R^2 of 0.567 indicating good fit.

Farmers using spacing >9 m are 6.5 times more likely to adopt systematically than those with spacing <4 m (OR = 6.528, $p < 0.001$). This reflects the biophysical reality that adequate spacing allows sufficient light penetration and reduces root competition. The strong effect of 9×9 m spacing (OR = 4.149) confirms this as the minimum spacing for effective intercropping, consistent with (Requier-Desjardins et al., 2024) . Farmers aged ≤30 years are 4.8 times more likely to adopt than those >60 years (OR = 4.791, $p < 0.001$), reflecting greater risk tolerance and openness to innovation among younger farmers.

High personal motivation increases adoption odds by 4.3 times (OR = 4.287, $p < 0.001$), positive personal beliefs by 3.8 times (OR = 3.838, $p < 0.001$), and strong social influence by 3.4 times (OR = 3.435, $p < 0.001$). These effects are larger than most technical variables, highlighting that adoption is fundamentally a social and psychological process. The stark difference between N'goussa (70% strong social influence, 70% high motivation) and Ouargla (10% strong social influence, 20% high motivation) explains much of the adoption gap between zones.
Extension contacts increase adoption odds by 3.4 times (OR = 3.435, $p < 0.001$), and professional membership by 2.4 times (OR = 2.401, p = 0.002). N'goussa, as an R&D site with regular extension contact and 63% professional membership, has the highest systematic adoption rate (64%). Farm type (new farm) increases adoption odds by 2.7 times (OR = 2.683, p = 0.001), and zone (N'goussa) by 3.1 times (OR = 3.074, $p < 0.001$). Water availability is not significant (p = 0.418), supporting that water quality and scheduling are more critical than mere availability. Credit access is marginally significant (p = 0.082), consistent with (Kim, 2025), who found financial constraints are not always the primary barrier. In Ouargla, socio-psychological factors outweigh credit constraints.

Table 9. Logistic regression results for systematic adoption (dependent variable: systematic adoption = 1, irregular = 0).

Variable	Coefficient (β)	Standard error	Wald χ^2	p-value	Odds ratio (exp β)	Marginal effect
Constant	-3.421	0.892	14.71	0.000	0.033	—
Technical factors						
Spacing (ref: <4 m)						
6×6 m	0.845	0.312	7.34	0.007	2.328	0.187
9×9 m	1.423	0.356	15.98	0.000	4.149	0.312
>9 m	1.876	0.421	19.86	0.000	6.528	0.398
Mixed spacing	0.567	0.398	2.03	0.154	1.763	0.126
Palm age (ref: >50 years)						
≤10 years	1.234	0.398	9.62	0.002	3.435	0.271
10-30 years	0.987	0.345	8.18	0.004	2.683	0.218
30-50 years	0.432	0.312	1.92	0.166	1.540	0.096
Water availability (1=available)	0.234	0.289	0.66	0.418	1.264	0.052
Human factors						
Farmer age (ref: >60 years)						
≤30 years	1.567	0.423	13.72	0.000	4.791	0.334
30-60 years	0.678	0.345	3.86	0.049	1.970	0.151
Education (years)	0.089	0.045	3.91	0.048	1.093	0.020
Farm type (1=new farm)	0.987	0.298	10.97	0.001	2.683	0.218
Organisational factors						
Extension contact (1=yes)	1.234	0.298	17.15	0.000	3.435	0.271
Professional membership (1=yes)	0.876	0.287	9.32	0.002	2.401	0.194
Credit access (1=yes)	0.543	0.312	3.03	0.082	1.721	0.121
Socio-psychological factors						
Positive beliefs (ref: negative)	1.345	0.298	20.38	0.000	3.838	0.293
Strong social influence (ref: low)	1.234	0.312	15.65	0.000	3.435	0.271
High motivation (ref: low)	1.456	0.325	20.08	0.000	4.287	0.314
Zone dummies (ref: Zone 01)						
Zone 02 (N'goussa)	1.123	0.298	14.20	0.000	3.074	0.248
Zone 03 (Sidi Khouiled)	0.456	0.287	2.52	0.112	1.578	0.102

Model fit statistics: Log-likelihood: -78.34, Cox & Snell R^2: 0.423, Nagelkerke R^2: 0.567 Hosmer-Lemeshow χ^2: 8.23 (p = 0.412) Percentage correctly predicted: 81.2%.
The logistic regression results confirm that spacing (especially >9 m, OR = 6.528), young farmer age (≤30 years, OR = 4.791), positive personal beliefs (OR = 3.838), high motivation (OR = 4.287), extension contact (OR = 3.435), and zone (N'goussa, OR = 3.074) are the strongest predictors of systematic adoption.

3.6 . Role of vegetation stratification

Figure 6 reveals a fundamental transformation in the vertical structure of oasis intercropping systems. The traditional three-stratum model (date palms + shrubs + herbaceous crops) now accounts for only 30-37% of farms across the

three zones. This decline is most pronounced in Ouargla (30%) and least pronounced in N'goussa (37%), reflecting varying degrees of traditional system preservation.
The dominance of two-stratum systems (37-48% of farms) represents pragmatic simplification driven by multiple pressures. Labour scarcity is a primary factor: three-stratum systems require management of three distinct vertical layers. As younger farmers migrate to urban areas (particularly evident in Ouargla), remaining farmers simplify to reduce labour demands. Water scarcity also plays a role: three-stratum systems have higher evapotranspiration, and with irrigation water increasingly limited, farmers prioritize water for date palms (the primary cash crop) and reduce understory complexity.
The persistence of single-stratum systems is highest in Ouargla (33%) and lowest in N'goussa (18%). The high rate in Ouargla confirms the decline of intercropping in this zone (67% adoption rate, compared to 82% in N'goussa). The low rate in N'goussa (18%) indicates that even when farms cannot maintain three-stratum systems, they maintain at least two-stratum systems rather than abandoning intercropping entirely. This shift toward vertical simplification raises concerns about long-term agrobiodiversity conservation.

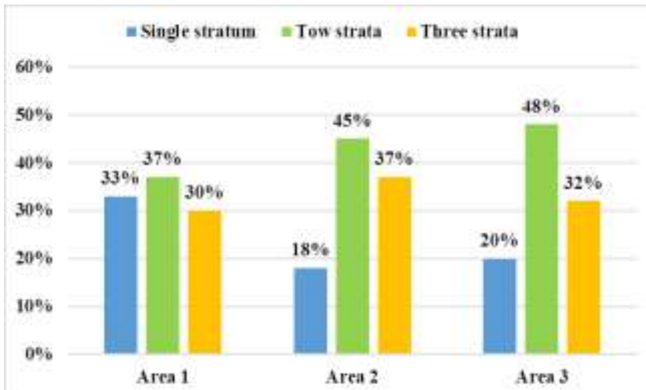

Figure 6. The distribution of farms is shown according to the number of plant strata (single, two or three strata) by area (Area 1: Ouargla; Area 2: N'goussa; Area 3: Sidi Khouiled).

Figure 7 shows the distribution of three distinct two-stratum models across the study zones. Model B (date palms + herbaceous crops) is the most consistent and stable model across all zones (30-33% of farms). This model represents the "minimal viable intercropping system" that maintains date production while providing diversification. The remarkable consistency across zones suggests this model represents a stable equilibrium balancing labour, water, and economic objectives. Farmers typically cultivate shade-tolerant crops such as spinach, purslane, and alfalfa. Model C (fruit trees + vegetable crops, no date palms) is the most innovative model, present only in N'goussa (10% of farms). This model substitutes date palms with faster-yielding fruit trees (citrus, vines, pomegranate, olive). Its emergence in N'goussa reflects young innovative farmers, strong social networks (70% strong social influence), access to extension services, and marketing opportunities for fresh fruit. The absence of Model C in Ouargla and Sidi Khouiled reflects different constraints: ageing farmers in Ouargla limit innovation, while Sidi Khouiled's government policies focus on date palm rehabilitation. Model A (fruit trees + herbaceous crops) is rarely adopted (4-5% in Ouargla and N'goussa, 16% in Sidi Khouiled). The higher rate in Sidi Khouiled (16%) reflects new farms where farmers chose fruit trees over date palms due to shorter time to first harvest (3-5 years for citrus versus 5-8 years for dates) or government subsidies.

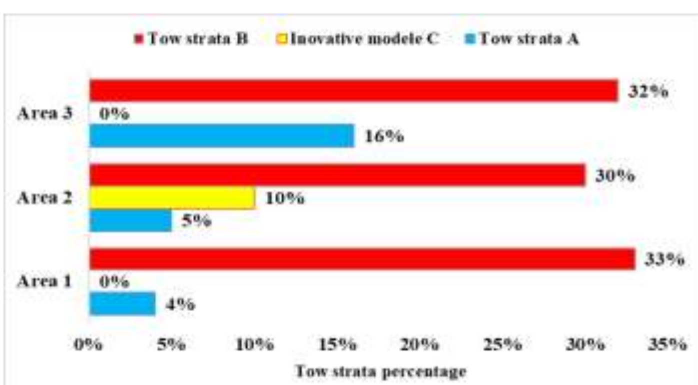

Figure 7: Two strata system combinations by area (Area 1: Ouargla; Area 2: N'goussa; Area 3: Sidi Khouiled).

4.Discussion

4.1. Adoption patterns and the integrated framework

The overall adoption rate of 75% confirms that intercropping remains a central strategy in oasis agricultural systems. However, the striking spatial disparities (82% in N'goussa, 74% in Sidi Khouiled, 67% in Ouargla) validate our integrated framework's premise that adoption is shaped by multiple interacting dimensions rather than any single factor.

4.2. Testing the hypotheses:

The findings provide robust support for the seven hypotheses examined.

H1 (Technical factors) was strongly confirmed: spacing showed the strongest association with adoption, particularly in Sidi Khouiled (V = 0.62) and N'goussa (V = 0.54). Logistic regression revealed that farmers using spacing >9 m were 6.5 times more likely to adopt systematically than those with spacing <4 m, aligning with (Requier-Desjardins et al., 2024). Palm age also showed strong effects: farmers with palms ≤10 years were 3.4 times more likely to adopt than those with palms >50 years.

H2 (Water availability) showed significant but weak-to-moderate associations in N'goussa (V = 0.27) and Sidi Khouiled (V = 0.26), but no significant relationship in Ouargla (V = 0.07). This counter-intuitive finding suggests water quality (salinity) and irrigation scheduling may be more decisive than mere availability in Ouargla, as noted by (Foufou& Bord, 2016; Laradj, 2017). Logistic regression confirmed water availability as non-significant (p = 0.418).

H3 (Human capital) was confirmed: younger farmers (≤30 years) were 4.8 times more likely to adopt systematically than farmers >60 years. Each additional year of education increased adoption odds by 9% (OR = 1.093, p = 0.048), corroborating(Kim, 2025).

H4 (Organisational factors) showed strong effects: extension contact increased adoption odds by 3.4 times (OR = 3.435, p = 0.000), and professional membership by 2.4 times (OR = 2.401, p = 0.002). Credit access was marginally significant (p = 0.082), consistent with (Kim, 2025).

H5 (Socio-psychological factors) produced among the strongest effects: positive personal beliefs increased odds by 3.8 times, strong social influence by 3.4 times, and high motivation by 4.3 times (all p = 0.000). The stark contrast between N'goussa (70% strong social influence, 70% high motivation) and Ouargla (10% strong social influence, 20% high motivation) explains much of the adoption gap.

H6 (Farm type) was confirmed: new farms were 2.7 times more likely to adopt systematic intercropping than old farms (OR = 2.683, p = 0.001). However, adoption objectives differ: old farms adopt for self-sufficiency (Bradai, 2002), while new farms adopt for economic objectives.

H7 (Vertical stratification) revealed the traditional three-stratum system is declining (30-37% of farms) in favour of two-stratum systems (37-48%). The innovative Model C in N'goussa (10% of farms: fruit trees + vegetable crops, no date palms) represents a genuine departure from tradition warranting careful monitoring.

4.3. Species diversity: implications for resilience and adaptation

The inventory of 57 intercropped species represents remarkable agrobiodiversity serving multiple functions. The high Shannon diversity index (H' = 3.89) and evenness (J' = 0.95) indicate that no single species dominates, buffering against pest outbreaks, disease, or market shocks.

The introduction of sunflower and panicum in 2023 demonstrates ongoing farmer experimentation. The absence of species disappearance during the study period (Table 3) is a positive indicator of system resilience. Zone-level differences are instructive: N'goussa (54 species) maintains the highest diversity, including industrial crops absent in Sidi Khouiled. Sidi Khouiled, despite having the highest intercropping adoption rate (76% of farms), has the lowest species richness (48 species), indicating simplification toward market-oriented vegetable and fruit production.

The Ouargla findings compare usefully with intercropping experiences in Xinjiang, China (Dai et al., 2017) and Africa(Kim, 2025). In Xinjiang, government-promoted intercropping of cotton with fruit trees led to farming income losses (1720922330 Yuan) due to low subsidies, insecure land tenure, resource competition, and labour intensity (30 man-days per field). In Ouargla, the decline in adoption and irregular practices in Ouargla suggest similar challenges. However, N'goussa's success demonstrates that intercropping can be economically viable when supported by strong social capital and endogenous innovation. The key difference appears to be endogenous innovation in N'goussa versus top-down implementation in Xinjiang.

(Kim, 2025) found that extension contact (coefficient 0.382), credit access (0.353), and livestock size (0.003) were significant adoption determinants. The Ouargla findings confirm the importance of extension contact (OR = 3.435) and credit access (marginally significant), but add socio-psychological dimensions (beliefs, social influence, motivation) as critical factors often overlooked. The gender finding (women more likely to adopt) contrasts with our male-dominated sample (82%), though species managed by women (purslane, herbs) suggest intra-household dynamics warrant further investigation.

4.4. Land tenure implications

Land tenure security emerged as a critical but incompletely measured factor in this study. In Xinjiang, (Dai et al., 2017) found that insecure land tenure was a primary reason for negative income impacts: farmers were unwilling to invest in fruit trees with life cycles exceeding remaining contract periods. In Ouargla, the distinction between old farms (customary tenure, often more secure) and new farms (state-granted usufruct rights, often for 30-50 years) likely influences investment incentives.

The innovative Model C in N'goussa (fruit trees + vegetable crops, no date palms) raises important tenure questions. Fruit trees require 3-7 years to reach productive age and can remain productive for 20-50 years. If farmers lack secure tenure beyond the typical contract period, they may be reluctant to invest in tree planting, explaining why Model C remains limited to 10% of farms in N'goussa and is absent elsewhere.

The logistic regression did not include a direct land tenure variable, but the strong effect of farm type (new farms: OR = 2.683) and zone (N'goussa: OR = 3.074) may partially capture tenure effects. Future research should include explicit measures of perceived tenure security and remaining contract years.

4.5. Policy implications and recommendations

The findings offer several policy implications for supporting intercropping as a strategy for oasis sustainability. In Ouargla, priority should be spacing optimisation (converting from <4 m to ≥9×9 m), palm grove rejuvenation, and support for ageing farmers. In N'goussa, focus on scaling successful innovations (Model C) through farmer-to-farmer extension. In Sidi Khouiled, address low professional membership (24%) to build social capital.

The strong effect of extension contacts (OR = 3.435) and professional membership (OR = 2.401) justifies continued investment in extension services and R&D sites, as demonstrated by N'goussa's success. The strong effects of beliefs (OR = 3.838), social influence (OR = 3.435), and motivation (OR = 4.287) suggest adoption is also a social and psychological process, requiring behavioural change communication and peer-to-peer learning.

The increasing adoption of olive, melon, and alfalfa needs market linkages, while the decline of tomato and red beet warrants investigation of pest management,clarify land tenure for tree planting regarding usufruct rights.Invest in water management focusing on salinity control and efficient irrigation, as water quality rather than availability constrains adoption (Laradj, 2017).

4.6. Limitations and future research directions

This study has several limitations. First, the cross-sectional design (2021-2024) captures adoption at a single period but cannot establish causality or track long-term trends. Panel data following the same farms over 10-20 years would be valuable. Second, the sample (180 farms) is adequate for bivariate analysis but limits the number of variables in multivariate models. Third, income and profitability data were not collected systematically, preventing direct comparison with the Xinjiang study. Fourth, land tenure was not measured directly, limiting analysis of tenure effects. Future research should address: (1) long-term economic impacts of intercropping, comparing old and new farms, systematic vs. irregular adoption, and different stratification models; (2) water productivity and water quality effects, particularly the water paradox in Ouargla; (3) land tenure security and its effects on tree planting investment; (4) market integration and value chains for intercropped products; (5) climate change adaptation through intercropping, including heat tolerance, water use efficiency, and carbon sequestration.

Conclusion

This study examined the dynamics of intercropping adoption in the Ouargla oases of southern Algeria, revealing intercropping as a widely practised activity (75% of farms) but one whose evolution depends critically on local context. The logistic regression model correctly predicted 81% of adoption outcomes, with socio-psychological factors showing the strongest effects (motivation OR = 4.287, beliefs OR = 3.838).

The inventory of 57 intercropped species represents remarkable agrobiodiversity (H' = 3.89, J' = 0.95), with vegetable crops (21 species), fruit trees (11 species), and fodder crops (8 species) being most important. Species diversity remains stable, with increasing adoption of market-oriented species demonstrating farmer adaptability. Vertical stratification is declining from the traditional three-stratum model toward two-stratum systems (3-48% of farms). An innovative two-stratum model combining fruit trees with vegetable crops (without date palms) has emerged on 10% of farms in N'goussa, showing promise for agro-ecological transition.

To support intercropping for oasis sustainability, public policies should: target technical assistance by zone, strengthen extension and farmer organisations, address socio-psychological barriers, support species diversification strategically, clarify land tenure for tree planting, and invest in water management (salinity, efficient irrigation).

The success of N'goussa demonstrates that intercropping can be economically viable and socially embedded when supported by strong social capital and intergenerational knowledge transfer. The decline in Ouargla serves as a cautionary tale of how urban pressure, ageing farmers, and water quality problems can undermine traditional systems. The innovative model emerging in N'goussa (fruit trees + vegetable crops) warrants careful monitoring to assess its long-term impacts.

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