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Evaluating Agricultural Sustainability in Permaculture Farms: A Multidimensional Approach for Resilient Farming Systems

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Abstract

Morocco's agriculture is increasingly constrained by climate change, water scarcity, and soil degradation, limiting the effectiveness of conventional farming. Permaculture offers a promising alternative, yet its sustainability in the Moroccan context remains underexplored. This study evaluates the multidimensional sustainability of permaculture farms and identifies key constraints to their resilience, assessing 20 farms in the commune of Brachoua using the IDEA (Indicators of Sustainability of Agricultural Farms) framework, adapted to local conditions through expert and farmer consultation. Scores were calculated across agroecological, socio-territorial, and economic dimensions. Farm typologies were identified using principal component analysis (PCA)—with adequacy confirmed by eigenvalues, Kaiser-Meyer-Olkin (KMO), and Bartlett's test—and hierarchical ascending classification (HAC), validated by dendrogram structure and silhouette index. Results show strong agroecological performance (65.1±8.5 points), moderate economic sustainability (61±13.5), and weak socio-territorial integration (41.15±12.2). PCA revealed two main axes explaining 85.4% of variance, while HAC distinguished two farm clusters: a small group of high-performing farms with stronger socio-territorial and economic linkages, and a majority cluster with average but uniform profiles. Weaknesses include limited livestock diversity, poor soil and water management, lack of product traceability, and weak community participation. The study concludes that while permaculture supports ecological sustainability and financial independence, socio-territorial deficiencies remain the main barrier. Targeted interventions—farmer training, cooperative development, and quality certification—are needed to improve outcomes. More broadly, the study shows the usefulness of combining IDEA with multivariate statistics to generate farm typologies, offering a transferable framework for assessing sustainability in smallholder systems facing climatic and resource challenges.

Keywords: agroecology; climate change adaptation; farm typology; multivariate analysis; sustainability assessment

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INTRODUCTION

Agriculture has long been criticized for its role in the depletion of natural resources and environmental degradation (Abdelhafidh et al., 2020). The dominant agricultural model, often described as "productivist," relies heavily on monoculture and the extensive use of chemical inputs such as fertilizers and pesticides. While these practices aim to maximize production to meet the demands of a growing global population (Bhati and Makanur, 2019; Hakimi and Brech, 2021), they have also led to significant environmental consequences, raising concerns about their long-term sustainability (Zurek et al., 2022). In the Moroccan agricultural context, resource overexploitation is most evident in the depletion of water reserves, the degradation of soils through erosion and nutrient loss, and the decline of biodiversity driven by monocultural practices and heavy reliance on chemical inputs (Hakimi et al., 2025). These pressures are particularly acute in semi-arid regions, where water scarcity combines with fragile soils to exacerbate environmental decline. This situation calls for a critical reassessment of conventional farming models and a transition toward more sustainable approaches that reconcile productivity with ecological integrity.

To address these challenges, agricultural systems must evolve to ensure both food security and resilience to climate change. Permaculture has emerged as a promising alternative, offering a sustainable agricultural model that seeks to minimize resource consumption while maintaining productivity and ecological balance (Jerner and Bitic, 2019). Developed in the early 1970s by Bill Mollison and David Holmgren (Marot, 2019), permaculture is defined as the conscious design and maintenance of agriculturally productive ecosystems that exhibit the diversity, stability, and resilience of natural ecosystems (Bhati and Makanur, 2019). Its main objective is to reduce dependency on external inputs while fostering ecological harmony (Verma and Tiwari, 2020). The approach emphasizes working with nature rather than against it (Centemeri, 2020).

Permaculture is guided by three fundamental ethics aimed at ensuring both environmental sustainability and human well-being (Geeraert, 2023). Earth care involves prioritizing environmental preservation, such as using organic fertilizers in optimal quantities instead of excessive chemical inputs (Anuhya, 2022; Fatima et al., 2023; Hakimi et al., 2024). People care ensures that basic human needs, including food, shelter, and social equity, are met while maintaining ecological balance (Verma and Tiwari, 2020). Fair share promotes responsible consumption and the redistribution of surpluses to those in need (Anuhya, 2022). These ethics are further operationalized through twelve design principles that guide human-nature interactions and ensure effective permaculture implementation (Nanni et al., 2021). These principles include observing natural patterns, capturing and storing energy, minimizing waste, integrating rather than segregating, and adapting to change through innovative solutions.

In Morocco, permaculture has gained traction as a viable alternative in response to water scarcity and the overexploitation of natural resources. The transition toward sustainable, environmentally friendly farming practices is now a necessity. Sustainable agriculture is a system that meets present and future food production needs while maintaining environmental health, economic viability, and social equity (Hakimi and Hamdoun, 2023; Naim et al., 2024). It extends beyond environmental concerns to encompass economic sustainability, social justice, and humane agricultural practices (Gustafson and Ingle, 1999; Zahm and Girard, 2023).

To effectively implement sustainable agriculture, robust sustainability assessment frameworks are required (Barbier and Lopez-Ridaura, 2010). Sustainability assessments guide decision-making by evaluating agricultural systems across three key dimensions: agroecological, socio-territorial, and economic. These dimensions reflect the complex, interdependent nature of farming systems and their interactions with local environments and communities. By identifying strengths and weaknesses within these dimensions, assessment tools support the development of context-specific strategies that promote long-term viability, resource efficiency, and social equity. Furthermore, they facilitate stakeholder engagement, enabling inclusive planning processes and adaptive management to address emerging challenges related to climate change, market volatility, and land-use pressures (Gaviglio et al., 2017).

Various methodologies have been developed to measure agricultural sustainability, with over 60 distinct assessment approaches documented

(Zahm et al., 2019). Among these, the IDEA method (Indicators of Sustainability of Agricultural Farms) stands out for its comprehensive, multi-criteria evaluation, making it particularly suited for region-specific assessments. This method evaluates sustainability across three dimensions—agroecological, socio-territorial, and economic—thus providing a holistic view of farming systems. Its adaptability to different contexts and ability to integrate both quantitative and qualitative indicators have contributed to its widespread use in academic research and policy-making. Moreover, it facilitates participatory evaluation involving local stakeholders (Hakimi and Hamdoun, 2023).

In addition to assessing sustainability at the farm level, this study makes a distinctive and timely contribution in two principal respects. First, it delivers clear methodological innovation by integrating the IDEA framework with advanced multivariate statistical techniques-principal component analysis (PCA) and hierarchical ascending classification (HAC)-to establish a typology of permaculture farms. Although such methods are well established in the classification of conventional and agroecological farming systems (Pépin et al., 2021; LaFevor, 2022; Hakimi et al., 2025), their application to permaculture remains almost absent, particularly in African contexts. This study, therefore, fills a critical methodological gap. Second, it generates rare and original empirical evidence from Morocco, where permaculture has emerged through grassroots initiatives in response to ecological degradation and chronic water scarcity, but in a policy vacuum devoid of structured governmental support, subsidies, or incentives. The systematic documentation of these experiences is not only overdue but essential, given the fragmented and limited state of empirical research on permaculture in Africa (Kruger, 2017; Didarali and Gambiza, 2019). By embedding Moroccan cases within broader international debates and applying a robust analytical framework, this research extends beyond descriptive analysis, exposing the agronomic, socio-territorial, and economic barriers that undermine sustainability while producing actionable, policy-relevant insights to inform the scaling up of resilient agricultural systems in semi-arid environments.

This study aims to conduct a comprehensive multi-criteria assessment of permaculture farms by analyzing their sustainability across agroecological, socio-territorial, and economic dimensions. The specific objectives are to diagnose the technical, socioeconomic, and environmental characteristics of permaculture farms, quantify their sustainability using the IDEA method, identify key strengths and weaknesses of permaculture practices, and determine the primary limiting factors affecting agricultural sustainability. The study tests the hypothesis that permaculture farms exhibit high agroecological sustainability but face limitations in socio-territorial and economic aspects, which may hinder their overall sustainability. By identifying critical constraints, this research seeks to contribute to the optimization of permaculture farming systems and inform policy recommendations for sustainable agricultural transitions.

MATERIALS AND METHOD

Study area and farm sampling

The rural commune of Brachoua, located within the municipality of Rommani in the province of Khémisset, in the Rabat-Salé-Kénitra region of Morocco, was selected as the study area. The region experiences a Mediterranean semi-arid climate, influenced by both maritime and continental oceanic factors, characterized by mild, moderately rainy winters and humid, temperate summers, with occasional Chergui winds. Brachoua is known for its agricultural diversity, including the cultivation of cereals, legumes, and oilseeds, alongside a thriving livestock sector, particularly sheep farming (Hakimi, 2021; Morel, 2022). The selection of Brachoua for this study is primarily due to its established reputation as a center for permaculture practices. Farmers in this area have embraced permaculture as a sustainable agricultural model, which supports food production and income generation while preserving natural resources. Additionally, the active participation of women in agricultural cooperatives underscores the socioeconomic dynamism of the region. Moreover, Brachoua has gained recognition as an ecotourism destination, combining sustainable agricultural practices with broader efforts for economic and cultural development (Morel, 2022).

The study focused on 20 permaculture farms (Figure 1), selected through a non-probabilistic, purposive sampling method (Gerville-Réache and Couallier, 2011). These farms, distributed across seven different “douars” within the commune, were chosen based on zoning techniques that optimize spatial organization by

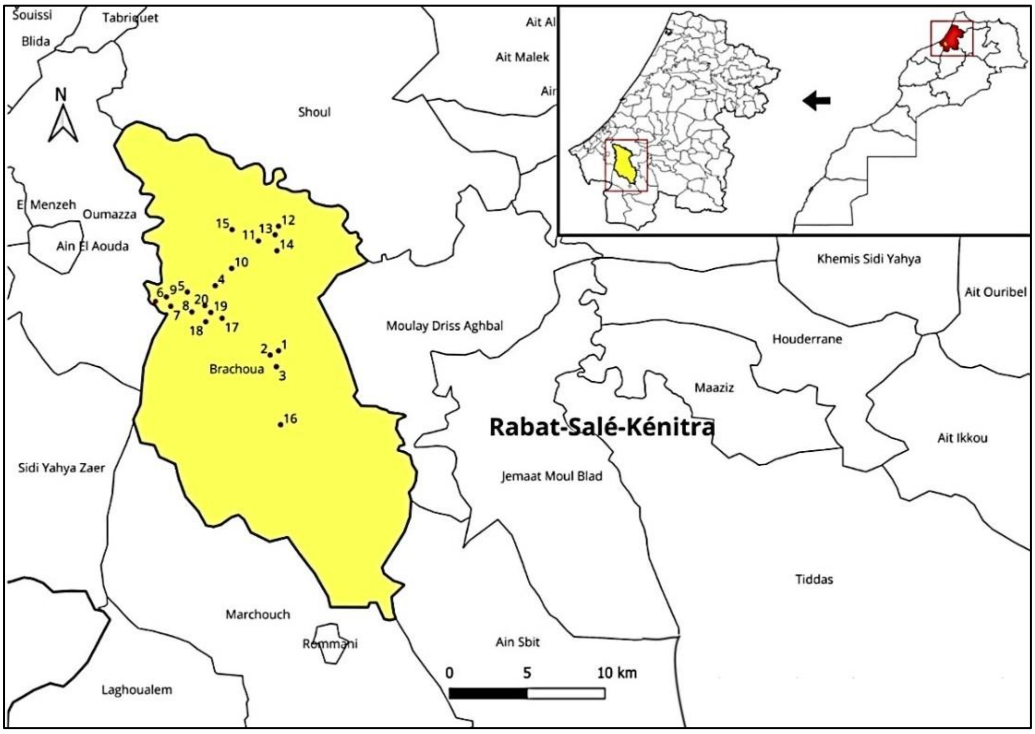

Figure 1. Geographic distribution of surveyed permaculture farms within the study area (commune of Brachoua)

Note: The map, generated using Quantum Geographic Information System (QGIS), highlights the spatial distribution of the 20 selected farms in the commune of Brachoua, Morocco. Symbols on the map represent individual farm locations, providing a visual overview of their geographical spread. The boundaries of the study region are delineated for context

placing frequently used and high-maintenance elements closer to the central area. This ensures efficient resource use while minimizing energy expenditure and travel distances, thereby enhancing system sustainability (Babac and Belić, 2018; Salleh et al., 2018).

The selection of 20 farms was determined by both methodological and logistical considerations. Given that permaculture in Morocco is still a relatively recent and localized practice, the overall number of farms practicing this system remains limited, with additional constraints linked to geographical dispersion and farmer availability. A purposive sampling strategy was therefore employed to ensure the inclusion of farms with demonstrated technical expertise, willingness to collaborate, and accessibility for repeated field visits. While the sample size was relatively modest, it encompassed the diversity of farm types currently present in the study area and captured sufficient variability across the agroecological, socio-territorial, and economic dimensions under investigation. Comparable sample sizes were adopted in previous exploratory assessments of alternative farming systems (Bir et al., 2019; Attia et al., 2021; Hakimi et al., 2025). Furthermore, the application of multivariate techniques such as PCA and HAC was appropriate in exploratory contexts where the objective was to identify patterns of differentiation rather than to generate statistically representative inferences (Gewers et al., 2021). Nevertheless, the limited number of farms imposed constraints on the generalizability of the findings to the broader Moroccan or regional context. The results should therefore be interpreted as indicative, providing a valuable empirical foundation upon which future studies with larger samples can build to strengthen external validity.

Presentation of the IDEA method: Justification for its choice and adaptation

The sustainability assessment was carried out using the IDEA method, known for its comprehensive approach to evaluating farm sustainability. This framework offers a multidimensional perspective on farm performance, considering agroecological, socio-territorial, and economic factors (Cruz et al., 2018; Ngo et al., 2021). The IDEA method serves as a valuable decision-support tool for farmers, allowing them to assess the sustainability of their operations at a specific moment and guiding them in transitioning towards organic and agroecological farming systems (Zahm and Girard, 2023). Originally developed in France, the IDEA method requires adaptation to the Moroccan agricultural context to ensure its applicability. This adaptation was necessary due to differences in climatic conditions, production systems, regulatory frameworks, and socioeconomic dynamics that shape Moroccan agriculture. The IDEA method was adapted to the Moroccan context to enhance methodological rigor through a participatory and iterative process. This adaptation built upon the tool's prior application and validation in previous studies conducted in Morocco (Hakimi and Hamdoun, 2023; Hakimi et al., 2025), providing a solid empirical foundation for its contextual refinement. Semi-structured consultations were conducted with key stakeholders, including local farmers, agricultural extension agents, and academic experts, to ensure that indicator selection and scoring criteria accurately reflected the agronomic and socioeconomic realities of Moroccan permaculture systems. Focus group discussions and expert validation rounds were employed to refine indicator definitions and weightings. For instance, the "product quality" indicator was adjusted following consultations with certification bodies and local cooperatives, whereas modifications to "crop diversity" were informed by farmers' practices and expert knowledge of regional cropping systems. Additionally, certain indicators, such as "quality of life", were excluded due to challenges in quantification and the cultural context, where self-assessment practices are less common among farmers. To further ensure validity and reliability, the adapted indicators were pre-tested on a subset of farms not included in the final sample, allowing the research team to assess internal consistency, verify scoring feasibility, and revise ambiguous items before full-scale data collection.

This participatory approach helped refine indicator selection and scoring criteria, ensuring that the model accurately represents the sustainability challenges and opportunities within Moroccan permaculture (Hakimi et al., 2025). The assessment framework was restructured to include 18 key indicators, grouped into nine components within the three core dimensions of agricultural sustainability. The method employed a standardized scoring system, known as the sustainability unit, which allows for the aggregation and weighting of indicators on a uniform scale. Scores ranged from zero to a predefined maximum, specific to each indicator, enabling a comprehensive and comparative evaluation of farm sustainability (Zahm and Girard, 2023) (Table 1).

Survey and data collection

A mixed-method approach was employed to assess sustainability in permaculture farms, integrating structured interviews with field observations. Data collection was conducted using face-to-face interviews with farmers, following the *Interview Papier et Crayon* (IPC) or Paper and Pencil methodology to ensure direct and accurate data recording. This approach minimized misinterpretations and allowed researchers to clarify questions when necessary while observing contextual factors in the field (Liebregts, 2023). A structured questionnaire consisting of 120 distinct questions was designed to capture both quantitative and qualitative information. It included closed-ended, multiple-choice, and open-ended questions to ensure a holistic understanding of farm operations, resource management, and sustainability practices. The questionnaire was carefully designed to facilitate precise and unambiguous responses, enhancing the reliability of the collected data (Saris and Gallhofer, 2014). Each farm underwent multiple site visits to ensure comprehensive data collection through a combination of surveys, in-depth interviews, and direct inspections. While the survey was administered once per farm, follow-up visits were conducted to engage with farm owners, managers, and local experts. On average, farms were visited 2 to 3 times, depending on participant availability and the specific data needed for the study. The data collection process spanned the entire 2023 to 2024 agricultural season, covering key farming activities such as soil preparation, planting, growth, and harvest. This longitudinal analysis provided an in-depth evaluation of seasonal variations, climate impacts, and farm-level decision-making processes (Du et al., 2024).

Data processing

The data collected from the farms were systematically processed and used to assign scores to sustainability indicators. Regardless of the original measurement units, all indicators were standardized according to the IDEA framework. Final sustainability scores for each dimension were calculated by summing the respective indicator scores. This structured dataset was then

Table 1. IDEA assessment framework tailored to the Moroccan context

Components		Indicators	Maximum values
		Agroecological dimension	
Diversity	A1	Crop diversity	18
	A2	Animal diversity	10
Space organization	A3	Plot management	12
	A4	Livestock and forage management	10
Farming practices	A5	Fertilization and organic matter management	18
	A6	Use of pesticides and veterinary products	10
	A7	Soil and water management	16
	A8	Energy dependency	6
		Socio-territorial dimension	
Product quality and promotion of the terroir	B1	Product quality	20
	B2	Valorization through short distribution channels	15
Jobs and services	B3	Contribution to employment	20
	B4	Social involvement	15
Ethics and human development	B5	Training and multi-activity	10
	B6	Reception, hygiene, and safety	20
		Economic dimension	
Viability	C1	Economic viability	20
	C2	Commercial vulnerability	30
Independence	C3	Financial independence	20
Efficiency	C4	Production process efficiency	30

Note: This table outlines the components, indicators, and corresponding maximum values used in the evaluation of permaculture farms within the Moroccan context. The agroecological, socio-territorial, and economic dimensions are represented, with specific indicators for each. The values are based on the maximum possible scores assigned to each indicator

compiled into an evaluation grid and formatted in Excel for further statistical analysis. A detailed statistical analysis was conducted to interpret the results. Key variables were summarized using descriptive statistics, which encompassed measures like means, medians, quartiles, standard deviations, and extreme values (minimum and maximum) (Johnson and Bhattacharyya, 2019; Cooksey, 2020).

PCA was performed to uncover underlying patterns and relationships. This method enabled dimensionality reduction while retaining essential information, offering a more detailed understanding of the intrinsic properties of the dataset (Gewers et al., 2021). The adequacy of PCA was confirmed through diagnostic tests: the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.62, above the minimum threshold of 0.5, while Bartlett's test of sphericity was highly significant ($\chi^2 = 356.24$; $p < 0.001$), indicating that the correlation matrix was suitable for factor analysis. Eigenvalues greater than one were retained, with the first two components explaining 85.4% of total variance. A scree plot confirmed the retention of these two components, and communalities showed that most variables were well represented (extraction > 0.6) (Nkansah, 2018; Shrestha, 2021; Ahmad, 2024).

Subsequently, HAC was employed to categorize farms into homogeneous clusters based on their sustainability performance. Ward's method applied to PCA factor scores produced a clear separation into two groups, supported by dendrogram interpretation. Internal validation confirmed this choice, as the silhouette coefficient (0.67) indicated good cohesion and separation. Testing three clusters reduced the silhouette score to 0.48, validating the two-cluster solution (Vázquez-González et al., 2024).

Finally, multicollinearity was examined before PCA to address potential redundancy among sustainability indicators. Variance inflation factors (VIFs) were below 3 for all variables, confirming the absence of problematic collinearity. All statistical processing was carried out using XLSTAT (2024), ensuring a comprehensive and multidimensional interpretation of the findings (El Ansari et al., 2016; Hakimi and Hamdoun, 2023).

RESULTS AND DISCUSSION

Analysis of the overall sustainability of permaculture farms

The three dimensions—agroecological, economic, and socio-territorial—were evaluated separately before aggregating them into an overall sustainability score to gain a comprehensive understanding of the sustainability performance of the surveyed permaculture farms. The highest sustainability score was observed in the agroecological dimension, with a mean value of 65.1±8.51, ranging from 51 to 79 points (Figure 2). The economic dimension followed closely, with an average score of 61±13.53, exhibiting greater variability, with values ranging from 25 to 90 points. In contrast, the socio-territorial dimension recorded the lowest score, which also determined the overall sustainability score of the permaculture farms, with a mean of 41.15±12.19 and a range of 28 to 81 points.

The box-and-whisker plots in Figure 3 illustrate the variability in sustainability scores across the agroecological, economic, socio-territorial, and overall (global) sustainability dimensions. Economic sustainability scores exhibit considerable variability, with a range of 45 and an interquartile range (IQR) of 15, indicating substantial disparities in economic performance among the studied permaculture farms. The agroecological sustainability dimension demonstrates lower variability, with scores more closely clustered around the median. The socio-territorial sustainability scores, however, present both low median and mean values, with noticeable variation and several farms exhibiting exceptional performance.

Data were analyzed using PCA followed by HAC to construct a typology of permaculture farms. Before running PCA, the adequacy of the data was tested. The KMO measure was 0.62, exceeding the 0.5 threshold for sampling adequacy, and the Bartlett's test of sphericity was highly significant ($\chi^2 = 356.24$; $p < 0.001$), confirming that correlations among indicators were sufficient for PCA. The analysis extracted two main components with eigenvalues > 1, together explaining 85.44% of the total variance. The scree plot confirmed a clear inflection after the second component, supporting the retention of two axes. Communality values were generally above 0.60, indicating that the majority of the variables were well represented by the selected components.

The results of the PCA provide valuable insights into the sustainability profiles of the permaculture farms, highlighting the multidimensional nature of sustainability and revealing distinct patterns of performance across the dimensions (Figure 4). The first two principal components, F1 (65.33%) and F2 (20.11%), accounted for 85.44% of the total variance. This robust representation of the data suggests that the sustainability dimensions assessed in this study are well captured by these principal axes, offering a clear and concise summary of the underlying structure of the sustainability performance of the farms.

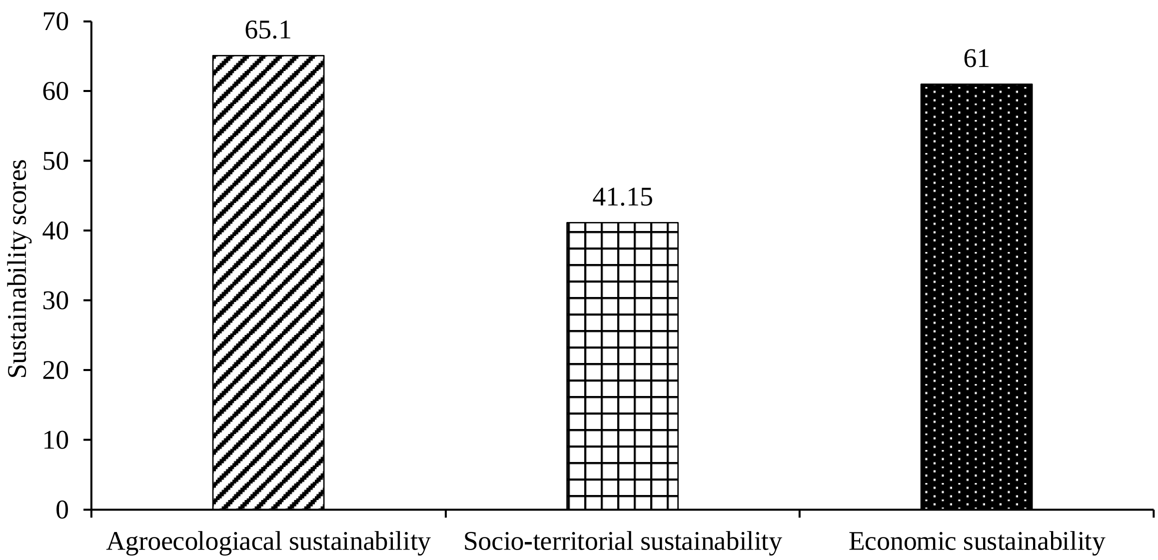

Figure 2. Overall sustainability scores across three dimensions for the studied permaculture farms

Note: Bar chart representing the overall scores for the three dimensions of sustainability-agroecological, economic, and socio-territorial, evaluated for the studied permaculture farms using the IDEA method

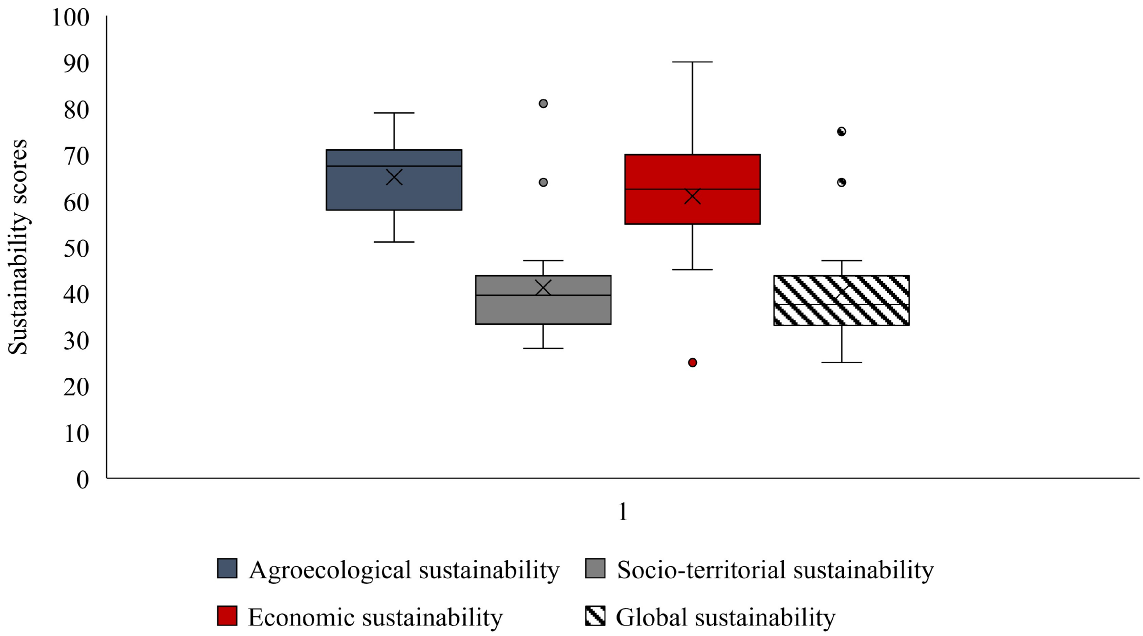

Figure 3. Distribution of scores in the three sustainability pillars and overall sustainability
Note: Box plot showing the dispersion of scores for agroecological, economic, socio-territorial, and overall sustainability among the studied permaculture farms. Each box represents the interquartile range, with the median indicated by the horizontal line and the mean represented by the "X" within each box. Whiskers extend to the minimum and maximum values within 1.5 times the IQR, while dots indicate exceptional values

The clustering of farms based on their PCA scores reveals significant variability in sustainability outcomes. Farms 1 and 16 are particularly notable for their distinctive sustainability profiles, positioned at the far right of the F1 axis, indicating superior socio-territorial and economic sustainability. In contrast, farms 6, 8, 9, 17, 18, 19, and 20 exhibit lower sustainability scores in socio-territorial and economic dimensions. The agroecological sustainability dimension, as represented by F2, reveals that farms 2 and 3 are positioned at the top of the F2 axis, demonstrating high scores in agroecological sustainability. This suggests that these farms place a strong emphasis on environmentally friendly practices, consistent with the core principles of permaculture. The relatively small cluster of farms positioned at the bottom of the F2 axis with lower agroecological sustainability scores indicates that while most farms maintain moderate to high agroecological performance, there remains room for improvement in this area. The overall clustering pattern observed in the PCA biplot suggests that the majority of permaculture farms tend to converge around the origin, reflecting average sustainability performance across all dimensions. While these farms share a common sustainability profile, farms 1 and 16 represent distinct cases of excellence, illustrating the potential for certain farms to serve as models for others seeking to enhance their sustainability practices (Figure 4). These high-performing farms could provide valuable case studies for identifying effective strategies and practices that contribute to exceptional sustainability outcomes.

The clusters were identified using HAC, a multivariate technique that groups objects based on their pairwise dissimilarities and progressively merges them into increasingly larger clusters. Ward's method was applied to the PCA factor scores to minimize intra-cluster variance and maximize inter-cluster differentiation. The dendrogram revealed the presence of two homogeneous groups corresponding to distinct farm profiles. This choice was validated by an average silhouette coefficient of 0.67, indicating satisfactory cohesion and separation of clusters. In contrast, a three-cluster solution produced a lower silhouette score (0.48), suggesting weaker stability and less robust typological boundaries. Figure 5 provides a visual representation of the hierarchical relationships, illustrating the degree of similarity and dissimilarity among the permaculture farms.

The clustering analysis identified two primary classes. Class 1 is composed of farms 1 and 16, which form a distinct subgroup characterized by exceptional sustainability metrics compared to the rest of the sample. This result aligns with the PCA findings, where farms 1 and 16 also emerged as high performers, particularly in the socio-territorial and economic dimensions. Class 2 encompasses the remaining farms, grouped into a single, relatively homogeneous cluster. Although minor variations exist among individual farms, their sustainability profiles converge around similar patterns. This consistency suggests that the core principles of permaculture are applied broadly across most farms, with only a few exceptional cases achieving markedly higher performance. The HAC and PCA analyses collectively highlight a clear distinction between a subset of high-performing farms and a broader group that aligns more closely with the mean sustainability profile.

For the overall sustainability of the studied permaculture farms, it is essential to consider the interconnections between economic, environmental, and social dimensions. The results highlight both strengths, such as financial independence and resource efficiency, and vulnerabilities, particularly in terms of income stability and market access. These findings align with previous research emphasizing the multidimensional nature of sustainability in alternative farming systems (Astier et al., 2012; Dumont et al., 2016). The substantial variability in economic sustainability scores reflects the uneven economic viability of the farms, influenced by factors such as limited production capacity, environmental constraints, and variations in resource management strategies. Similar findings were reported by Bir et al. (2019) where small-scale sustainable farms in Algeria demonstrated significant economic heterogeneity due to market access limitations and external environmental factors. Additionally, research by Smith et al. (2014) highlights that the financial sustainability of agroecological farms is often constrained by fluctuating yields, limited government support, and high labor requirements.

The relative uniformity in agroecological sustainability scores suggests that the studied farms adopt consistent agroecological practices, likely due to shared environmental conditions and widespread application of ecological farming principles. Gómez-Limón and Sanchez-Fernandez (2010) confirm that agroecological farming systems tend to exhibit greater uniformity in sustainability scores due to reliance on diversified, resilient agricultural practices and resource-efficient methods that mitigate external

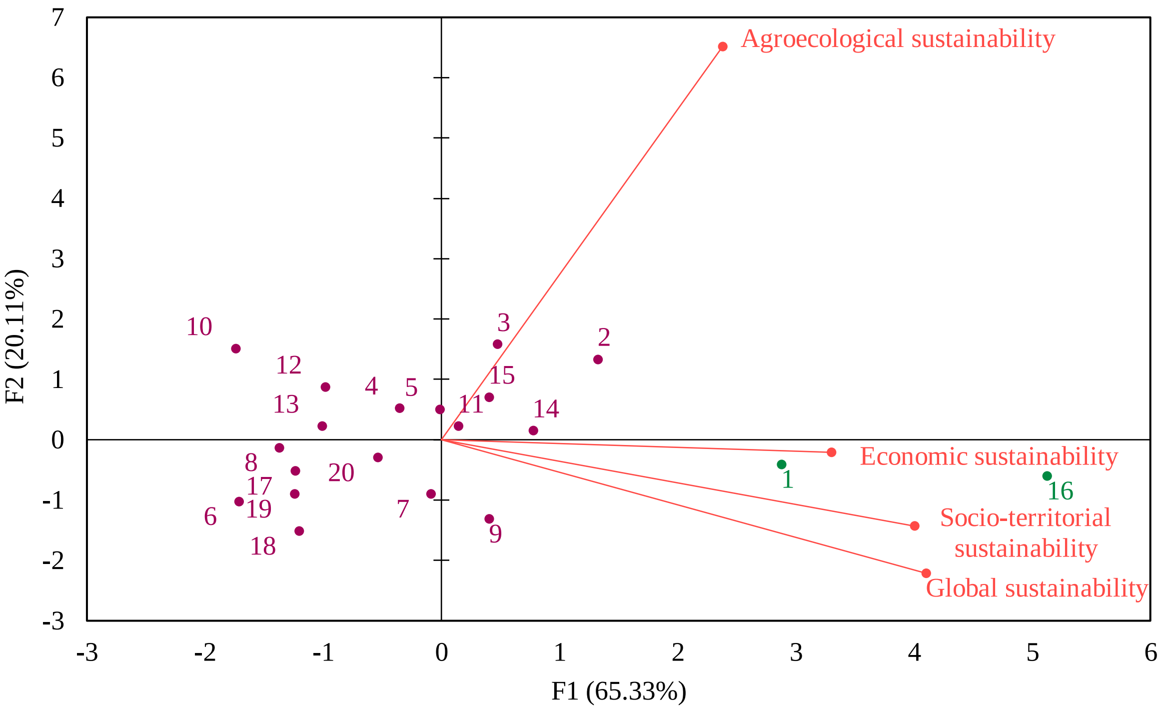

Figure 4. Biplot of PCA for permaculture farms and agricultural sustainability scales

Note: The plot shows the relationships between farms (data points) and sustainability metrics (vectors), with the principal components (F1 and F2) capturing the largest variances in the dataset. Clusters of farms suggest similar sustainability practices, while the orientation and length of the sustainability scale vectors indicate their influence on the principal components

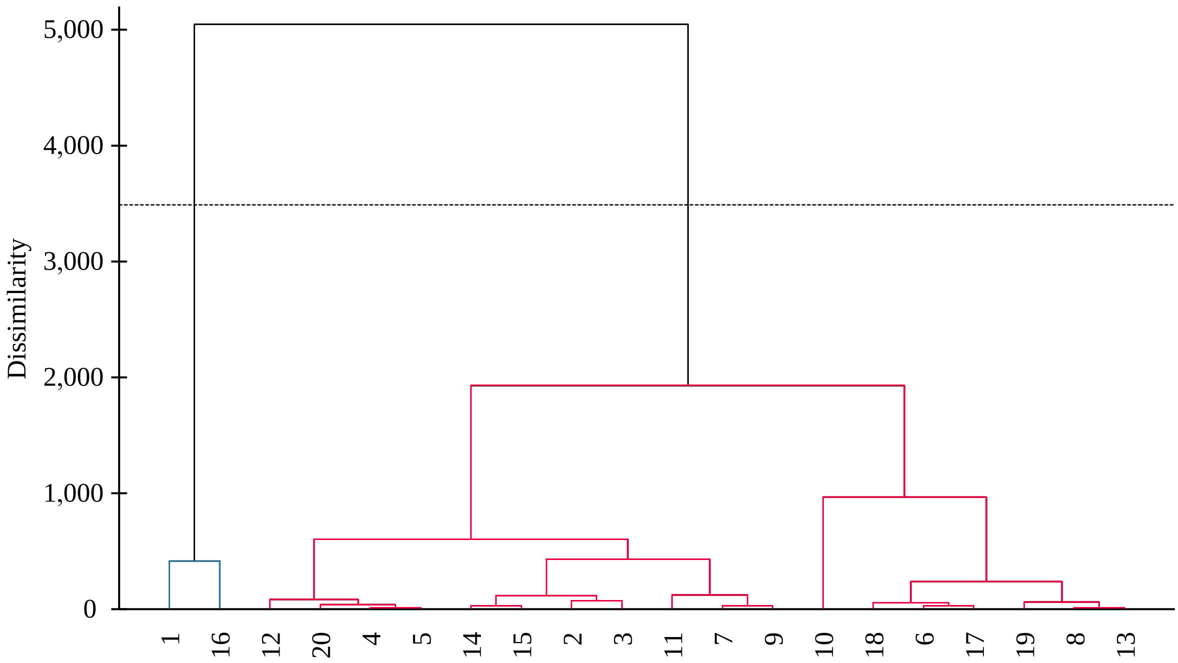

Figure 5. Hierarchical clustering of permaculture farms based on agricultural sustainability scales
Note: The dendrogram illustrates the hierarchical structure of similarities (or dissimilarities) among the farms, divided into two main classes: Class 1, which includes farms 1 and 16, highlighting their distinct high performance on the socio-territorial and economic scales, as observed in the PCA biplot; and Class 2, which encompasses all other farms, suggesting generally similar sustainability performances across the remaining farms

shocks. Furthermore, Attia et al. (2021) found similar agroecological sustainability trends in Tunisia, attributing them to the adoption of conservation farming techniques and permaculture principles.

In contrast, the socio-territorial sustainability scores highlight significant challenges in achieving social integration and territorial cohesion within the studied farms. These findings resonate with those of Van Zanten et al. (2014), identifying social isolation and weak institutional support as key barriers to sustainability in small-scale agroecological systems. Addressing these issues may require targeted interventions aimed at strengthening community engagement, fostering local networks, and enhancing farmer support systems, as suggested by Pretty and Bharucha (2014), who emphasize the role of participatory governance and collective action in improving rural sustainability outcomes.

For the socio-territorial dimension, the data exhibit a range and interquartile range nearly identical to those observed for overall sustainability, suggesting that this dimension serves as a limiting factor in the agricultural sustainability of permaculture farms. The indicator scores for this scale are concentrated around the median, suggesting a relatively uniform performance across the studied farms from a socio-territorial perspective and highlighting its influence on overall agricultural sustainability. These results corroborate the work of Hakimi et al. (2025), who reported a score of 45.3 points. Similarly, Hakimi and Hamdoun (2023) identified the socio-territorial scale as the primary constraint in the sustainability of rainfed agroecosystems. Comparable results were also observed by Attia et al. (2021) for small dairy farms in northern Tunisia, where the socio-territorial dimension scored 28.02 points. However, Najjar et al. (2021) reported a different pattern, noting that the agroecological dimension was the most limiting, with a score of 52 points for a cattle farm.

These findings underscore the importance of enhancing the socio-territorial dimension to better integrate permaculture farms within their social and environmental landscapes. This aspect directly influences farmers' quality of life by encompassing human development, product quality, and contributions to employment and local services. Strengthening it could significantly improve overall farm sustainability by fostering social cohesion, economic stability, and environmental responsibility. To achieve this, targeted interventions are essential. Policies should emphasize farmer training, expand access to local and national markets, and encourage cooperative networks for stronger economic and social ties. Additionally, greater support for certification programs and value-added processing can boost product recognition and marketability, enhancing farm viability (Hakimi and Brech, 2021; Attia et al., 2022). A comprehensive approach that incorporates socio-territorial sustainability into broader agricultural strategies would help build a farming system that is more robust and sustainably balanced (Altieri et al., 2015; Knickel et al., 2021).

The use of PCA and HAC to reveal the hierarchical relationships between farms underscores how different farms can be categorized based on their sustainability practices. The clear division into two primary classes suggests that, while a dominant cluster of farms shares similar sustainability profiles, certain farms stand out for their significantly stronger sustainability performance. Farms 1 and 16's distinction as high performers in both HAC and PCA analyses suggests that specific sustainability factors—such as socio-territorial and economic sustainability—play a crucial role in farm performance. Their superior practices may stem from factors like strong community engagement or better market integration. This aligns with previous studies linking socioeconomic factors with enhanced sustainability outcomes in agricultural systems (Dale et al., 2013; Lamine, 2015).

The homogeneity within Class 2 suggests that permaculture principles, such as ecological design and resource efficiency, are being consistently applied across most farms. While minor variations exist, they do not substantially impact the overall sustainability profile. This supports the effectiveness of permaculture practices in promoting sustainability (Vitari and David, 2017) but also indicates potential areas for improvement, particularly in agroecological practices. The relatively small variations observed suggest that while permaculture systems are broadly successful, there remains room for further adaptation to local conditions (Yadav et al., 2023).

The distinction between high-performing farms and the broader cluster highlights the diversity within the permaculture community. While the convergence in sustainability practices across most farms is encouraging, the identification of exceptional cases offers valuable insights into how socioeconomic and territorial factors can drive enhanced sustainability (Morenés et al., 2018). These standout examples illustrate the potential for refining and adapting permaculture practices to strengthen overall performance.

Although the statistical validation favored a two-cluster solution, exploratory examination of the HAC dendrogram and sustainability scores suggests the possible existence of an intermediate group. This group would likely correspond to farms with average socio-territorial integration but gradually improving agroecological and economic performance, placing them between the high-performing farms (Class 1) and the more uniform group (Class 2). Such transitional farms may represent systems in the process of adopting more diversified practices, strengthening market integration, or engaging more actively in community networks. Although the third cluster was less statistically robust, recognizing its potential enriches the interpretation by highlighting the dynamic nature of sustainability trajectories. From a policy perspective, supporting these "in transition" farms through targeted training, cooperative organization, and certification schemes could accelerate their movement toward higher sustainability performance and broaden the base of successful permaculture models (Skrzypczyński et al., 2021; Zhang, 2024). Future studies with larger datasets, broader regional coverage, and longitudinal monitoring could better capture such transitional profiles and provide more nuanced insights into the pathways by which farms progress toward sustainability.

Overall, the global sustainability scores reflect the cumulative influence of the three key dimensions—agroecological, economic, and socio-territorial. While strong agroecological performance contributes positively to sustainability, persistent weaknesses in economic and socio-territorial aspects constrain the full potential of permaculture farming systems. These results highlight the need for a holistic and integrated strategy that promotes balanced progress across all dimensions, as emphasized by previous studies advocating the simultaneous consideration of environmental, economic, and social factors in alternative farming systems (Wezel et al., 2009; Gliessman, 2018).

The current study further examined how these three sustainability dimensions vary across farm types identified through PCA and HAC analyses. Class 1, comprising high-performing farms (farms 1 and 16), exhibited superior socio-territorial engagement and economic autonomy alongside robust agroecological practices, indicating that the integration of social cohesion, market orientation, and ecological management underpins overall sustainability. In contrast, Class 2 displayed relatively uniform agroecological performance but lower socio-territorial and economic scores, suggesting that, although ecological principles are broadly implemented, limitations in community engagement, market access, and income stability restrict overall sustainability.

Although the focus of this study is on permaculture farms, the observed constraints, particularly in socio-territorial cohesion and economic resilience, are consistent with broader patterns in smallholder agriculture within similar semi-arid contexts (Van Zanten et al., 2014; Bir et al., 2019), suggesting that certain limitations are system-wide rather than exclusive to permaculture. These findings underscore the utility of the clustering approach for identifying differentiated pathways toward sustainability enhancement and for informing context-specific policy and management strategies (El Ansari et al., 2016; Aribi et al., 2022; Hakimi, 2022).

Analysis of three sustainability scales for permaculture farms

Agroecological dimension

The agroecological dimension was assessed through three main components: diversity, space organization, and farming practices. Each component encompassed several sustainability indicators (Table 2), evaluating agricultural practices in terms of productivity, environmental respect, and natural resource protection—key pillars of permaculture principles.

The permaculture farms studied demonstrated strong performance across the agroecological dimension. Notably, the indicator “A6-Use of pesticides and veterinary products” achieved a perfect score of 10 points (100% of the maximum theoretical score) across all farms, reflecting the absence of chemical treatments and phytosanitary products. Similarly, the “A3-Plot management” indicator scored 98.33% of its maximum theoretical value, attributed to the small farm sizes (≤ 2 ha), which facilitated spatial organization and diversification of cultivated species.

Regarding diversity, the “A1-Crop diversity” indicator scored 68.33% of the theoretical maximum, highlighting the presence of multiple crop species, including cereals, legumes, vegetables, arboriculture, forage, and medicinal plants. In contrast, the “A2-Animal diversity” indicator presented a lower score of 3.5 out of 10 (35%), indicating limited diversity in livestock systems. Approximately 35% of farms raise only one animal species, 25% have two species, and 30% maintain three species, with sheep, cattle, and laying hens being the most common. This limited variety reduces the potential for multifunctional livestock integration, which could otherwise enhance ecological resilience and productivity.

Table 2. Agroecological sustainability components and indicators for the permaculture farms under study

	Components	Indicators		Avg±SD	Range
	Title	Code	Title		
Agroecological dimension	Diversity	A1	Crop diversity	12.3±3.63	0-18
		A2	Animal diversity	3.5±2.04	0-10
				15.8±3.99	0-28
	Space organization	A3	Plot management	11.8±0.62	0-12
		A4	Livestock and forage management	4.2±2.50	0-10
				16.0±2.60	0-22
	Farming practices	A5	Fertilization and organic matter management	13.2±4.23	0-18
		A6	Use of pesticides and veterinary products	10.0±0.00	0-10
		A7	Soil and water management	6.0±3.78	0-16
		A8	Energy dependency	4.1±0.45	0-6
				33.3±7.16	0-50
			Total	65.1±8.51	0-100

Note: The table presents the average (Avg)±standard deviation (SD), and range of values for each agroecological component and corresponding indicator. Statistical analysis includes standard error analysis and the ranges of values across the farms for each indicator, providing a comprehensive view of the variation in sustainability practices and outcomes across the studied permaculture systems

The “A4-Livestock and forage management” indicator scored 42%, suggesting inefficiencies due to high livestock density (> 2 livestock units (LU)) and limited grazing areas (< 10% of total farmland). The “A7-Soil and water management” indicator had the lowest score, achieving only 37.5% of its theoretical maximum. Around 70% of the surveyed farms scored less than half of the maximum possible value, largely due to reliance on tillage, lack of irrigation infrastructure, and absence of anti-erosion measures. Finally, the “A8-Energy dependency” indicator showed relatively strong results, scoring 4.1 out of 6 points (68.33%), with 95% of farms reaching at least 66.67%, primarily due to the limited use of gas and oil for pumping energy.

The agroecological performance of the studied permaculture farms demonstrates notable strengths, reflecting adherence to the core principles of ecological farming (Gissler, 2023). One of the most significant achievements is the high score related to pesticide and veterinary product use, underscoring a strong commitment to organic practices and the elimination of synthetic inputs. These findings are consistent with previous results from Hakimi et al. (2025) in organic systems, and they surpass those reported by Bir et al. (2019) and Attia et al. (2022), who recorded lower sustainability scores for similar indicators (45.4% and 54.92%, respectively).

Other areas of strength are plot management and spatial organization. The high score under the “A3-Plot management” indicator reflects effective land-use strategies, particularly in small farms (< 2 ha), which promote polyculture and optimize resource use. These results align with those of Hakimi and Hamdoun (2023), who found a direct correlation between plot organization and improved sustainability outcomes.

Despite these positive aspects, certain challenges persist, particularly in livestock integration and soil/water resource management. The “A4-Livestock and forage management” score remains relatively low (42%), pointing to issues such as overstocking and insufficient pastureland. Similar concerns have been raised by Hakimi and Hamdoun (2023) and Attia et al. (2022), emphasizing the need for improved forage strategies, such as rotational grazing and better pasture planning, to ensure sustainability in integrated systems.

Likewise, soil and water management emerged as a critical weakness, with low scores for the “A7-Soil and water management” indicator. Deficiencies in anti-erosion practices and inefficient irrigation systems highlight a vulnerability that could undermine long-term sustainability. These results echo those reported by Hakimi and Hamdoun (2023), who observed even lower scores (8.13%) in rainfed agroecosystems. As emphasized by Powlson et al. (2011), improving soil conservation practices is essential for ensuring the resilience of sustainable farming systems.

In contrast, the farms demonstrated strong performance regarding energy dependency, with results indicating significantly lower reliance on fossil fuels. This performance exceeds that reported by Bir et al. (2019) (45.6%) and Attia et al. (2022) (14.5%), suggesting that energy efficiency is a key strength in the studied systems. Minimizing fossil fuel inputs enhances the resilience of permaculture farms, especially in the context of climate change and rising energy costs (Krebs and Bach, 2018).

To strengthen the linkage between observed agroecological practices and permaculture ethics, it is important to consider the principles of “people care” and “fair share,” which emphasize equitable resource distribution, social responsibility, and stewardship of natural systems (Mollison, 1988; Mollison and Holmgren, 2021). While biodiversity is addressed through crop diversification, the limited livestock diversity and constraints in forage management reflect potential trade-offs between land availability, labor resources, and cultural preferences regarding animal husbandry. Many farms maintain only one or two livestock species, often due to small plot sizes, fragmented landholdings, or prioritization of crop production for household consumption and market sale. These practices suggest that socioeconomic and labor-related factors influence the extent to which multifunctional livestock systems are integrated, highlighting a need for strategies that reconcile ecological objectives with practical farm-level limitations. Addressing these gaps could involve promoting rotational grazing, diversified forage cultivation, and community-based livestock initiatives, thereby enhancing both ecological resilience and alignment with permaculture principles while respecting farmers’ capacity and cultural context.

Socio-territorial dimension

The socio-territorial dimension of the permaculture farms assessed comprises three key components: “product quality and promotion of the terroir”, “ethics and human development”, and “jobs and services” (Table 3). This dimension provides valuable insights into farmers’ quality of life, their engagement in human development, and their degree of social integration. However, results indicate that this is the weakest sustainability pillar, with a mean score of 41.15±12.19, thereby acting as a limiting factor for the overall sustainability performance of the farms.

This dimension includes several indicators, among which contrasting results were observed. A particularly critical weakness is the “product quality” indicator, which scored only 1.25±4.55 out of 20, representing 6.25% of its theoretical maximum. This extremely low result reflects the absence of traceability and quality assurance systems such as certification, labeling, or product control mechanisms. In contrast, the “valorization through short distribution channels” indicator showed encouraging results, with an average score of 10.4±2.70 out of 15, and 85% of the farms relying on local or direct marketing strategies. This approach supports better consumer connection and local economic integration, partially offsetting the lack of formal quality systems.

On the jobs and services front, the “contribution to employment” indicator scored 7.5±3.72 out of 20, revealing that most farms generate limited employment beyond family labor. The “social involvement” indicator, with an average of 7.95±3.36 out of 15, highlights relatively low engagement in cooperative or associative structures. This limits access to collaborative marketing channels, knowledge sharing, and institutional support—factors that could otherwise contribute to greater socioeconomic resilience.

The ethics and human development components show a mixed performance. The “training and multi-activity” indicator scored just 1.55±2.72 out of 10, pointing to a lack of access to agricultural training, continuing education, and complementary activities such as agrotourism or processing. These are missed opportunities for income diversification and capacity building. However, the “reception, hygiene, and safety” indicators scored more favorably, with an average of 12.5±3.17 out of 20 (62.5% of its theoretical maximum). Most farms appear to comply with basic hygiene standards and have minimum infrastructure in place for visitor reception and waste management.

Overall, the low performance in several socio-territorial indicators underlines important structural challenges faced by permaculture farms. The absence of quality assurance mechanisms, limited education levels, and weak institutional and community ties constrain the development potential of these systems. Addressing these weaknesses through stronger partnerships with public institutions and research bodies could provide access to training, technical advice, and financial mechanisms. This, in turn, would enhance farmers’ ability to diversify their activities, improve their market access, and build more resilient and socially integrated farming models.

Table 3. Socio-territorial sustainability components and indicators for the permaculture farms under study

	Components	Indicators		Avg±SD	Range
	Title	Code	Title		
Socio-territorial dimension	Product quality and promotion of the terroir	B1	Product quality	1.2±4.55	0-20
		B2	Valorization through short distribution channels	10.4±2.70	0-15
				11.6±5.44	0-35
	Jobs and services	B3	Contribution to employment	7.5±3.72	0-20
		B4	Social involvement	7.9±3.36	0-15
				15.4±5.64	0-35
	Ethics and human development	B5	Training and multi-activity	1.5±2.72	0-10
		B6	Reception, hygiene, and safety	12.5±3.17	0-20
				14.0±5.47	0-30
			Total	41.1±12.19	0-100

Note: The table presents the socio-territorial sustainability components, their corresponding indicators, and the average (Avg)±standard deviation (SD) for each indicator, as well as the observed range of values for each. The ranges provide an overview of the variation observed across the farms for each indicator. Statistical measures were computed based on data from the studied farms, and error analysis was performed to ensure precision in reporting the mean values and associated variations

The analysis reveals several critical weaknesses in the socio-territorial dimension of the studied permaculture farms, alongside a few promising practices that offer opportunities for improvement and replication. A significant area of concern is the low score for “B1-Product quality”, which highlights deficiencies in quality control, traceability, and standardization. These findings are consistent with previous research showing that the lack of structured quality assurance frameworks undermines consumer trust, product marketability, and farm competitiveness (Murphy et al., 2022; Mishra and Singh, 2023). The introduction of quality certification systems, such as organic labeling or geographic indications, could play a pivotal role in enhancing transparency and market access (Mishra and Singh, 2023).

Another major limitation is the low level of farmer participation in training programs and associative structures. This restricts their access to technical knowledge, financial tools, and networking opportunities, all of which are essential for sustainable development. Prior studies (Šūmane et al., 2018; Kachali and Chimonyo, 2024) emphasize that training initiatives focused on sustainable practices, business development, and cooperative management significantly improve farmer capabilities. Moreover, farmer cooperatives and local food networks have been shown to boost economic resilience, fair trade practices, and social cohesion (Sotamenou et al., 2018). Encouraging greater participation in associative frameworks, producer groups, and certification programs can strengthen collaboration, knowledge sharing, and collective bargaining power. Additionally, forming partnerships between farmers, research institutions, and government agencies is vital for providing technical support and exploring diversification pathways such as agrotourism and educational farm visits, which enhance socioeconomic sustainability (Hakimi et al., 2025).

Despite these challenges, the results also point to positive performances in specific indicators. Notably, the relatively high scores for “B2-Valorization through short distribution channels” and “B6-Reception, hygiene, and safety” reflect successful practices that reinforce the socio-territorial fabric of permaculture farms. The widespread use of short food supply chains strengthens direct links between farmers and consumers, boosting market resilience, trust, and product visibility (Michel-Villarreal, 2023). Furthermore, good hygiene practices and infrastructure for waste management and food safety contribute to both social well-being and environmental stewardship (Alaka and Ogunlade, 2024).

Scaling up these successful strategies and promoting peer-to-peer learning among farmers can help replicate these results across the broader farming community. Overall, a comprehensive approach is needed to improve the socio-territorial sustainability of permaculture farms. Key strategies should include implementing quality management frameworks, expanding access to training programs, and fostering farmer networks. These measures can contribute to greater economic viability, stronger social cohesion, and enhanced long-term resilience of permaculture farming systems (Vigne et al., 2017; Hakimi and Hamdoun, 2023).

Economic dimension

The economic dimension of sustainability comprises three key components: viability, independence, and efficiency. This study evaluates the financial outcomes of permaculture farms, focusing on cash flows and financial independence (Table 4).

Permaculture farms exhibit an intermediate level of economic sustainability, with significant

Table 4. Components and indicators of economic sustainability for the permaculture farms under study

	Components	Indicators		Avg±SD	Range
	Title	Code	Title		
Economic dimension	Viability	C1	Economic viability	8.5±4.62	0-20
		C2	Commercial vulnerability	12.0±4.97	0-30
				20.5±6.86	0-50
	Independence	C3	Financial independence	19.0±4.47	0-20
	Efficiency	C4	Production process efficiency	21.5±8.75	0-30
	Total			61.0±13.53	0-100

Note: The table presents the average (Avg)±standard deviation (SD) and the range of values for each component and indicator of economic sustainability. The data provide insight into the economic viability, independence, and efficiency of the farms, illustrating variability across the studied sample variation among farms. The viability component (20.5/50 points, or 41% of the theoretical maximum) reveals uneven performance. While some farms demonstrate high viability, others report lower incomes, with nearly 50% of farms earning below the Guaranteed Minimum Agricultural Wage (SMAG) of 88.57 MAD per day or 2,303.08 MAD per month. About 40% report incomes between one and two times the SMAG. The indicator for economic viability (C1) scores 8.5/20 points (42.5% of the theoretical maximum), while commercial vulnerability (C2) scores 12/30 points (40%), reflecting a general exposure to market fluctuations and limited diversification of clientele.

Several factors contribute to these low incomes, including reduced agricultural production due to drought, water scarcity, and crop losses caused by environmental pressures such as wild boar incursions, flooding, and rabbit infestations. These findings highlight the need for adaptive strategies, such as diversified income sources, improved water management techniques, and sustainable pest control methods, to mitigate financial risks.

Despite these challenges, permaculture farms exhibit strong financial independence (C3), achieving 19/20 points (95% of the theoretical maximum), signifying minimal reliance on external financing. Moreover, they demonstrate high efficiency in their production processes. The efficiency component (C4) scores 21.5/30 points (71.67% of the theoretical maximum), reflecting their use of local seeds, minimal tillage, reliance on family labor, and the absence of chemical treatments.

Overall, the economic dimension of sustainability for permaculture farms reaches 61/100 points, or 61% of the maximum theoretical value, underscoring a moderately sustainable economic profile with notable strengths in independence and efficiency, alongside vulnerabilities in market exposure and income generation.

Economic sustainability is fundamental to the long-term viability of permaculture systems. The results indicate a complex interplay between viability, independence, and efficiency, where financial autonomy and resource optimization emerge as pillars of resilience (Attia et al., 2021). Similar findings in North African contexts support this relationship, emphasizing that minimizing external input use while maximizing local resource efficiency enhances financial stability (Bir et al., 2019; Hakimi and Hamdoun, 2023).

The analysis reveals that economic vulnerability is strongly influenced by environmental uncertainties, including climate variability, pest pressure, and limited natural resources. These external stressors echo the challenges reported in Tunisia and Algeria, where unpredictable climatic conditions reduce farm productivity and financial performance (Bir et al., 2019; Attia et al., 2021). To address these risks, farms must adopt adaptive strategies, such as diversifying income sources, implementing efficient water management practices, and relying on ecological pest management methods. Such approaches can reduce exposure to environmental shocks and contribute to more stable farm incomes.

Another critical challenge is market dependence, as reflected in the high commercial vulnerability score (40%). This issue mirrors the findings from other rainfed agroecosystems, such as those in Morocco's Zaër region (Hakimi and Hamdoun, 2023). Small-scale permaculture farms often lack access to diverse and stable markets, resulting in revenue instability.

To address this, a shift toward alternative marketing channels is recommended, including community-supported agriculture (CSA) models, direct-to-consumer sales, and cooperative marketing structures for shared branding and logistics. In addition, digital platforms and e-commerce tools offer new opportunities to expand market reach, reduce dependency on intermediaries, and build stronger customer relationships.

In contrast to these vulnerabilities, one of the most encouraging findings is the high economic efficiency score (71.67%), which surpasses those observed in conventional systems (Attia et al., 2022; Hakimi and Hamdoun, 2023). This reflects the strong self-sufficiency and resource optimization inherent in permaculture systems. By minimizing reliance on costly external inputs such as synthetic fertilizers and commercial seeds, these farms demonstrate resilience to both economic and environmental disruptions. Such efficiency supports long-term viability and can buffer farms against fluctuations in input prices or supply chain disruptions. To improve the economic sustainability of permaculture farms, a dual strategy is essential: reinforcing internal resilience through self-sufficiency and efficiency, while simultaneously reducing external vulnerabilities related to market access and environmental risks. These integrated efforts will contribute to more resilient, profitable, and sustainable farming systems (Krebs and Bach, 2018).

Building on these insights, the current study provides one of the first systematic evaluations of permaculture farms in Morocco, offering important contributions to understanding their sustainability performance across agroecological, socio-territorial, and economic dimensions. The combined use of the IDEA framework and multivariate analyses (PCA and HAC) enabled the identification of distinct farm clusters and generated actionable knowledge to inform both practice and policy. Nonetheless, certain limitations should be acknowledged. The relatively small and geographically constrained sample reflects the limited number and dispersion of permaculture farms in Morocco, and the purposive sampling strategy may have led to an overrepresentation of particular practices. Moreover, some socio-territorial indicators relied on qualitative judgments and self-reported information, which may introduce subjectivity. Future research could address these constraints by expanding the geographic scope, including larger and more representative samples, and implementing longitudinal monitoring to validate and refine the findings across diverse farming contexts.

CONCLUSIONS

Socio-territorial sustainability is the main constraint, largely due to gaps in quality management, traceability, and farmer training. In contrast, strong agroecological performance, reflected in diversified crop patterns, effective soil and water management, and integrated pest management, together with high economic autonomy, characterized by income self-sufficiency and reduced reliance on external inputs, highlights the potential of these farms to support sustainable agricultural systems. Addressing socio-territorial gaps is therefore essential to improving overall sustainability. The study's findings underscore the importance of integrated interventions across the three sustainability pillars—agroecological, economic, and socio-territorial—to achieve long-term, resilient outcomes. High-performing farms demonstrate how the combination of ecological management, social integration, and economic autonomy can guide broader sustainable practices, while lower-performing farms highlight areas where targeted support can accelerate progress. The recommendations can be framed across different time horizons to enhance practical outcomes. In the short term, interventions should focus on farmer training in quality management, traceability, and direct marketing. Medium-term actions include supporting cooperative networks, improving access to farm inputs, and promoting transitional farms identified through the cluster analysis. Long-term strategies encompass institutional reforms related to certification systems and traceability, infrastructure development for climate adaptation, and policies aimed at strengthening socio-territorial cohesion. Aligning these interventions with the farm cluster typology ensures that strategies are context-specific and can effectively foster differentiated pathways toward sustainability.

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