

Article

Digitalizing Sustainability Assessment in Agriculture: The SUSTIN-OLIVA Indicator-Based Application for Tunisian Olive Farming Systems Under Agroecological Transition

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Abstract

With the shift in Tunisian olive growing toward more intensive models, significant sustainability concerns have emerged. Aware of the need for reliable and operational tools to support agricultural policies under climate and socioeconomic pressures, we address a digitalized methodological framework for measuring and assessing the sustainability of olive farming systems that are undergoing an agroecological transition. The main contribution lies in the development of the SUSTIN-OLIVA digital indicator-based application, designed as a decision-support tool to enhance the accessibility, scalability, and operationalization of sustainability assessment within a holistic approach that integrates environmental, economic, and socio-territorial indicators tailored to Tunisian olive agroecosystems. The methodology was tested on 61 Tunisian olive farms in two agroecological zones undergoing transition, using face-to-face surveys conducted between April and May 2026 with a structured questionnaire. Principal Component Analysis (PCA) was applied as an exploratory approach to examine the relationships, contribution patterns, and internal structure of the proposed sustainability indicators. The results indicated that, among the 28 indicators considered, 23 made substantial contributions to the main patterns of variation identified by the PCA in the studied context. These findings demonstrate the feasibility and operational applicability of the SUSTIN-OLIVA framework across heterogeneous olive farms and provide insights into differences in sustainability performance and indicator interactions. The framework also enables the identification of under-addressed sustainability dimensions, supporting more targeted interventions and context-specific decision-making. Overall, this work advances digitalized sustainability assessment by linking a holistic indicator framework with an operational digital decision-support tool, thereby supporting adaptive governance in the Mediterranean olive sector.



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Keywords: SUSTIN-OLIVA application; digitalized sustainability assessment; olive farming systems; agroecological transition; PCA; Tunisia

1. Introduction

The global agricultural sector is undergoing profound transformations in response to increasing climate, economic, and social pressures, including climate change, resource scarcity, environmental degradation, labor constraints, and the growing need to ensure sustainable food production [1–4]. These challenges have reinforced the need for effective approaches to assess and support the sustainability of farming systems. Because agricultural sustainability encompasses interconnected environmental, economic, and social dimensions, its assessment requires the integration of diverse indicators and sources of information [3–6]. At the farm level, sustainability assessment tools are increasingly viewed not only as instruments for measuring performance, but also as means of structuring sustainability information and supporting strategic management decisions [3,5–7]. In this context, digitalization provides new opportunities to improve data collection, integration, analysis, and communication, thereby facilitating the operational use of sustainability information in agricultural decision-making [7,8]. However, the contribution of digital tools to sustainability ultimately depends on how effectively they are integrated into agricultural management and decision processes [9,10].

In Tunisia, olive cultivation plays a central role in the national agricultural economy and rural livelihoods [11]. The sector represents a major component of the country's agri-food exports [12] and covers nearly 1.96 million hectares, with considerable agrobiodiversity and socio-ecological value [13,14]. At the same time, the progressive intensification of olive production, including monocropping and super-high-density systems, has generated increasing environmental pressures such as soil degradation, water stress, biodiversity loss, and reduced agroecosystem resilience [15–18]. These pressures reinforce the need for olive farming systems to undergo a transition toward more sustainable and agroecological production models [19].

Such a transition requires assessment approaches capable of translating the multi-dimensional concept of sustainability into measurable and actionable information. Sustainability indicators have therefore become essential instruments for simplifying system complexity, organizing heterogeneous information, and supporting evidence-based decision-making [20,21]. Over the past decades, several indicator-based and multicriteria frameworks have been developed for agricultural sustainability assessment [21–26]. IDEA (Indicateurs de Durabilité des Exploitations Agricoles) and RISE provide multidimensional assessments at farm level, while SAFA, developed by the FAO, addresses governance, environmental integrity, economic resilience, and social well-being. MESMIS adopts a systemic and participatory approach, whereas TAPE specifically addresses the multidimensional assessment of agroecological transitions. These frameworks have substantially advanced sustainability assessment; however, their implementation may involve complex data requirements and analytical procedures, which can constrain accessibility, scalability, and practical use, particularly in data-scarce contexts [27,28]. Reviews of farm-level sustainability assessment tools have also highlighted substantial diversity in methodological choices, data requirements, complexity, and intended uses, with some approaches providing only limited connections between assessment results and subsequent strategic decision-making [29,30]. Moreover, applying generic frameworks to specific agricultural sectors and geographical contexts may require adaptation of indicators and assessment criteria to adequately capture the characteristics of local farming systems. Previous adaptations

of sustainability assessment approaches to Tunisian olive farms and the contextualization of SAFA indicators illustrate the importance of incorporating sector- and context-specific characteristics into sustainability assessment [24,25].

This need for contextualization is particularly relevant to Tunisian olive farming, which occupies more than one-third of the country's arable land and nearly 80% of the area devoted to tree crops, making the sector strategically important for the agricultural economy and rural territories [11–14]. Tunisian olive farming systems are characterized by substantial variability in production conditions and management practices, including fluctuations in yields and prices, deficit irrigation and soil management constraints, opportunities for olive by-product valorization, and challenges related to the control and valorization of the olive value chain. Against this background, SUSTIN-OLIVA was developed as a farm-level sustainability assessment framework specifically tailored to Tunisian olive systems. It integrates environmental, economic, and socio-territorial indicators selected to reflect the specific characteristics and sustainability challenges of olive agroecosystems undergoing agroecological transition.

Digitalization can further enhance the operationalization of such context-specific sustainability assessment frameworks by facilitating standardized data collection, the integration and processing of heterogeneous information, and the communication of assessment results to users [31–35]. At farm level, the usefulness of a digital sustainability assessment tool depends not only on its ability to calculate indicators, but also on its capacity to organize and communicate results in a form that can support decision-making [30,36]. Digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and data platforms are increasingly being applied to agricultural monitoring, resource-use efficiency, precision management, and decision support [33,34,37,38]. Recent developments in IoT- and AI-based sensing technologies further illustrate the potential of digitalization to generate and process field-level information for agricultural management [39]. Nevertheless, digitalization should not be considered an end in itself; rather, it should function as an enabling layer that improves the accessibility, integration, interpretation, and use of sustainability information within existing agricultural decision processes [9,10].

Despite the growing use of digital technologies for agricultural monitoring, precision management, resource optimization, and environmental assessment, their integration into comprehensive, multidimensional sustainability assessment remains comparatively limited. Existing digital applications demonstrate the potential of digitalization to operationalize sustainability indicators in different agricultural systems, including farm-level applications in livestock and other production contexts. However, these approaches differ considerably in their methodological foundations, assessment scope, and integration of environmental, economic, and social dimensions. Furthermore, the availability of a digital assessment tool does not, by itself, demonstrate improved sustainability outcomes; evidence on the longer-term contribution of digitalization to sustainability and resilience remains limited, particularly in African smallholder farming contexts [40]. More specifically, the integration of a crop-specific, multidimensional sustainability assessment framework into a dedicated digital application for olive farming systems remains insufficiently documented. This gap is particularly relevant in Mediterranean olive-growing regions, where climatic and resource constraints are increasing while farming systems are undergoing substantial structural and technological changes. There is therefore a need for operational digital tools that can translate context-specific, multidimensional sustainability frameworks into accessible and structured decision-support applications at farm level.

Against this background, this study develops and applies SUSTIN-OLIVA, a digital, indicator-based framework designed to assess sustainability in Tunisian olive farming systems undergoing agroecological transition. The study focuses primarily on the sustain-

ability indicator system and examines the contribution and interrelationships of individual indicators across the environmental, economic, and socio-territorial dimensions. Using farm-level data collected through the SUSTIN-OLIVA application, the analysis explores the internal structure of the proposed indicator system and identifies patterns of stronger and weaker contributions among the indicators in the studied context. The analysis also considers sustainability patterns at farm level. The objective is therefore not only to operationalize sustainability assessment through a digital environment, but also to generate structured evidence on the contribution of sustainability indicators and their interactions, thereby supporting the identification of strategic priorities for agricultural management and territorial decision-making.

The contribution of this study lies in linking a crop- and context-specific sustainability indicator framework with an operational digital assessment environment while maintaining a clear focus on the analytical value of the indicators. By examining indicator contributions and interrelationships across the three sustainability dimensions, SUSTIN-OLIVA provides a structured basis for identifying sustainability priorities that can inform extension services, stakeholders, and policymakers. In this perspective, the application serves not merely as a digital interface for data collection, but as an operational decision-support environment that connects farm-level sustainability information with broader priorities for agroecological transition in Tunisian olive-growing territories.

2. Materials and Methods

This study was conducted within the framework of the Sustainable Intensification of Food Production through Resilient Farming Systems in West and North Africa (SustInAfrica) project, which aims to support the transition of smallholder farms and SMEs toward sustainable intensification. In line with this objective, the present research focuses on the digitalization of sustainability assessment through the development and deployment of a digital, indicator-based decision-support application for olive farming systems.

The methodological approach builds on a systems perspective promoted by the SUSTIN-OLIVA framework, integrating sustainability indicators within a digital environment to improve data collection, standardization, and analytical processing. The use of a digital platform enhances the implementation of sustainability assessment by enabling structured data capture, improving comparability across farms, and facilitating scalable analysis under heterogeneous conditions.

Overall, the proposed framework contributes to the development of operational tools supporting evidence-based assessment and decision-making for more resilient and sustainable agricultural systems in the southern Mediterranean context.

2.1. Study Area

The method was tested in two contrasting agroecological zones in Tunisia: Béja (north-west) and Sousse–Monastir (central-east coast). The selection of these two areas was designed to test the feasibility, practical applicability, and the preliminary performance of the digital assessment framework across contrasting production and environmental conditions, while capturing differences in farming systems, resource availability, and climatic constraints.

Béja, in northwestern Tunisia, is predominantly characterized by a sub-humid Mediterranean bioclimatic stage, with mild winters and relatively high annual rainfall, ranging from approximately 530 to 650 mm, compared with the central-eastern Sahel. The mean annual temperature is around 17.5 °C, with monthly mean temperatures ranging from 9.3 °C in January to 27.2 °C in August. These relatively favorable climatic conditions support diversified, predominantly rainfed farming systems, in which olive cultivation,

mainly the Chetoui variety, is integrated with cereals and other crops. Olive groves covered approximately 36,100 ha in 2025.

In contrast, Sousse–Monastir, located in the Tunisian Sahel, is characterized by a semi-arid Mediterranean bioclimatic stage, with lower and more irregular rainfall, around 300–330 mm per year, and higher mean annual temperatures of approximately 19–20 °C, ranging from about 11.6 °C in winter to 28.2 °C in summer. Olive farming is more widespread and increasingly intensified, covering approximately 152,523 ha in 2025, and is increasingly associated with complementary irrigation that rely predominantly on groundwater.

These differences in climatic conditions, water availability, farming intensity, and resource-use patterns create distinct agroecological contexts for olive farming. At the same time, both areas are increasingly exposed to climate change, including rising temperatures, rainfall variability, prolonged dry periods, and recurrent droughts. This contrast provides a relevant basis for examining how the selected sustainability indicators capture differences in farm structure, resource use, and sustainability-related practices across farms operating under different agroecological and resource-use constraints. The indicator framework can therefore be applied under different environmental and farming conditions. Overall, the study illustrates the potential of a digital indicator-based approach to support structured sustainability assessment in Mediterranean olive farming systems.

2.2. Data Collection and Sampling Strategy

Data were collected from a total of 61 olive farms, including 31 farms in Béja, 30 farms in the Sousse–Monastir region, and one reference farm located in Béja. The reference farm, characterized by ongoing bio-diversification practices, is included within the 31 farms surveyed in Béja and was considered a pilot farm for this study. It implements a wide range of sustainability-oriented practices, including rural tourism, active collaboration with research and development stakeholders, value-chain integration through its own olive mill and bottling activities, and certified organic farming. The farm also serves as a field site for experiments on sustainable practices, including crop diversification, composting of by-products, and livestock integration. These characteristics provided a real-world basis for designing and validating the indicators, ensuring that they reflect feasible and practically implementable sustainability practices. A face-to-face survey was conducted with olive farmers between April and May 2026 using a structured questionnaire to collect the data used in this study.

A purposive sampling strategy was adopted to capture the diversity of olive farming practices rather than to ensure statistical representativeness. Because no reliable sampling frame was available for olive farms engaged in agroecological transition, farms were identified through the networks and contacts of local agricultural development services, facilitating access to farms that met the study criteria. Farm selection was primarily based on their engagement in an agroecological transition process, with efforts made to include diverse crop associations and agricultural practices to reflect different farming configurations. This approach aimed to generate a heterogeneous dataset suitable for assessing the applicability of the proposed digital sustainability assessment framework.

Data were processed using the SUSTIN-OLIVA digital application deployed on tablets, enabling real-time data entry, standardized responses, enhanced data quality, and the immediate generation of sustainability assessment results.

The collected data cover indicators across the three main dimensions of farm sustainability: environmental, economic, and socio-territorial. The computation of indicators and the structured database are automatically generated by the application. The de-

tailed set of indicators and the functioning of the digital application are presented in the following sections.

2.3. Methodological Framework

The methodology is based on a set of indicators covering the main dimensions of sustainability and implemented through the SUSTIN-OLIVA application, which constitutes the core digital tool of this study. The indicator selection was guided by three complementary pillars: (i) an in-depth review of existing sustainability assessment methods [2,25,41,42]; (ii) the multidisciplinary expertise of the research team, combining extensive knowledge of the Tunisian olive sector, particularly olive farming systems undergoing agroecological transition, with expertise in indicator-based sustainability assessment and digitalization; and (iii) extensive fieldwork and data-collection activities conducted in the study areas, including stakeholder workshops and field-based interactions with local actors involved in olive farming and agroecological transition. These field activities provided empirical insights into local farming practices, constraints, priorities, and sustainability challenges, thereby contributing to the contextualization of the indicator framework. Further information on the participatory activities conducted within the study areas is available through the SustInAfrica project webpage (<https://sustinafrica.com/> accessed on 28 August 2026).

The development and parameterization of the scoring framework were further informed by empirical studies conducted in the Tunisian agricultural context, particularly [24,41,43], as well as by empirical and experimental insights gained from the reference farm. This combination of scientific literature, multidisciplinary expertise, empirical evidence, field-based knowledge, and stakeholder engagement ensured that the SUSTIN-OLIVA design was not directly transferred from a generic sustainability framework, but specifically adapted to the characteristics, challenges, and realities of the Tunisian olive farming systems investigated in this study.

This research represents an original contribution to the evaluation of olive farming systems undergoing an agroecological transition. Its relevance is both practical and methodological, as it advances the refinement of sustainability measurement tools within a digital environment. Such approaches are increasingly recommended [41,44] in a policy context where sustainability strategies emphasize the internalization of externalities through incentive mechanisms, subsidies, and credit schemes aimed at promoting agroecological practices.

The approach combines quantitative and qualitative methods to capture both tangible and intangible dimensions of olive farming systems undergoing agroecological transition, within a broader process of digitalizing sustainability assessment through the development of the SUSTIN-OLIVA application. It is structured into three main steps (Figure 1):

Step One consists of the design of a comprehensive and holistic indicator-based framework covering the environmental, economic, and socio-territorial dimensions of sustainability. Beyond the identification of indicators, this step establishes a methodological protocol for their calculation, scoring, and aggregation into an integrated sustainability assessment using weighted criteria. The questionnaire implemented in SUSTIN-OLIVA was developed in accordance with this indicator framework and underwent several rounds of pre-testing on the reference farm. This iterative process enabled the identification and refinement of potential redundancies, ambiguities, inconsistencies, and errors, while improving the clarity, coherence, and operational suitability of the questionnaire prior to field implementation.

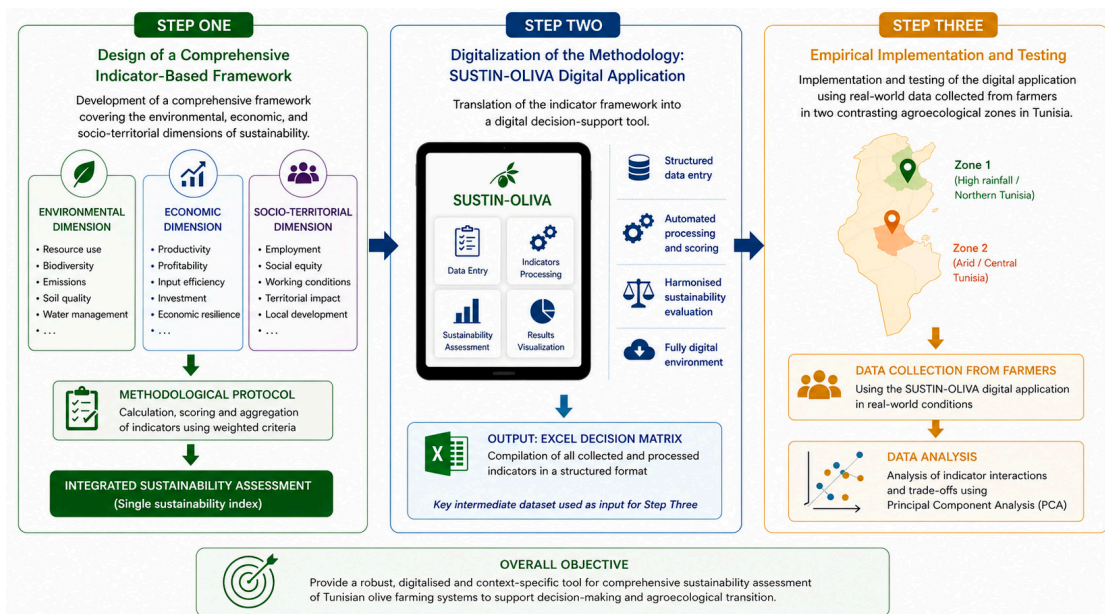


Figure 1. Overall structure of the methodological approach.

Step Two focuses on the digitalization of the proposed methodology through the development of the SUSTIN-OLIVA digital application. This step translates the indicator framework into an operational decision-support tool, enabling structured data entry, automated processing, and harmonized sustainability evaluation in a fully digital environment. The application also generates outputs in the form of an Excel decision matrix, which compiles all collected and processed indicators in a structured format. This matrix serves as a key intermediate dataset for subsequent analysis and is directly used as input for the third step of the methodology.

Step Three involves the empirical implementation and preliminary assessment of the digital application using real-world data collected from farmers in two contrasting agroecological zones in Tunisia. The application was tested under field conditions to assess its feasibility, practical applicability, and operational performance and to identify potential constraints arising during data collection. Given the limited and sometimes unreliable availability of internet connectivity in rural farming areas, the application was specifically designed to support offline data collection, allowing questionnaires to be completed and data to be recorded without requiring a continuous internet connection. This field implementation provided an initial assessment of the applicability of the digitalized framework under contrasting farming conditions, rather than constituting a statistical validation of its robustness or generalizability. The collected data were also used to analyze indicator interactions and potential trade-offs using Principal Component Analysis (PCA).

2.3.1. SUSTIN-OLIVA Indicator-Based Method–Concept and Indicators

The SUSTIN-OLIVA Indicator-Based Method introduces a substantial set of indicators considered relevant and necessary to assess sustainability. This indicator package, as previously mentioned, is grounded both in an extensive review of existing literature and in the expertise of the research team, which brings in-depth knowledge of the Tunisian olive sector and experience in indicator-based sustainability assessment. As such, this work represents a significant contribution to the literature, particularly in relation to evaluating the sustainability of olive farming systems undergoing agroecological transition. The proposed methodology is referred to throughout the article as SUSTIN-OLIVA (SUSTainability framework IN agroecological OLIVE farming systems).

SUSTIN-OLIVA is a measurement system composed of indicators and their respective assessment calculation tools, which include both quantitative calculations and a scoring system explained for each intangible indicator.

The selection of criteria and indicators for each sustainability dimension is based on the following sustainability hypotheses:

Hypothesis 1. *Overall sustainability emerges from the concurrent and balanced consideration of its three interrelated dimensions: socio-territorial, economic, and environmental. In olive farming systems undergoing ecological transition, the three sustainability dimensions appear complementary and mutually reinforcing rather than conflicting. Our analysis highlights the strong structural coherence among them, indicating that improving one dimension often supports the others. This synergy suggests that ecological transition can foster resilience without requiring trade-offs between profitability, social cohesion, and environmental care.*

Hypothesis 2. *Characterization of economic sustainability in the context of the olive farming system under agroecological transition. An olive farming system in agroecological transition is economically sustainable if it ensures an acceptable level of income, enables savings, and stabilizes revenues through diversified income sources along the value chain and through the creation of added value. Such a system reduces income-related risks—whether due to market fluctuations, climate hazards, or input availability.*

Hypothesis 3. *Characterization of environmental sustainability in the context of the olive farming system under agroecological transition. An olive farming system in agroecological transition is environmentally sustainable if it adopts agroecological principles and circular economy practices, and promotes efficient water use in the production process (i.e., high water productivity).*

Hypothesis 4. *Characterization of socio-territorial sustainability in the context of the olive farming system under agroecological transition. A socio-territorially sustainable olive system contributes to local embeddedness and territorial dynamics, supports short supply chains, promotes corporate social responsibility (CSR) among olive enterprises, and guarantees farmers' quality of life. It should also support employment generation—especially for women and youth—ensuring decent work conditions.*

These hypotheses represent the foundation for a comprehensive understanding of what constitutes a sustainable olive farming system in agroecological transition.

A sustainable olive system under agroecological transition meets the needs of current and future generations by balancing across three key components—soil, water, and plants. It ensures the long-term viability of the olive tree (over 50 years), preserves the soil as the basis for future agricultural activity, and promotes rational water management—a critical concern in Tunisia. It also promotes the valorization of by-products such as pruning residues, olive pomace, and wastewater—aiming for a zero-waste model that combines economic value with reduced environmental harm, especially from toxic effluents like olive mill wastewater. Socio-territorially, it supports decent local employment, values traditional knowledge, fosters territorial development, and preserves landscapes and cultural heritage. It also encourages generational renewal by making farming attractive to the youth. Economically, it seeks to maximize income and reduce costs through product diversification and value enhancement; addressing key challenges, notably the bulk sale of olive oil. In conclusion, a sustainable olive farming system under agroecological transition is one that is economically viable and profitable, generates positive environmental impacts, and contributes meaningfully to territorial development. The criteria and indicators can be visually represented through Figure 2.

Goal	Dimensions	Criteria	Indicators
Overall sustainability	Socio-territorial	Dynamic local territorial anchorage	→ Good governance → Valorization of local know-how → Involvement in community life → Valorization through a quality label → Multifunctionality of agriculture
		Valorization through short supply chains	→ Valorization through short supply chains
		Corporate Social Responsibility	→ Corporate Social Responsibility
		Farmers' quality of life	→ Farmers' quality of life
		Job creation and retention / Inclusion of women, youth, and decent work	→ Share of women among workers → Share of young people (< 40 years old) among workers → Job formalization and decency → Capacity building
		Territorial anchoring	→ Territorial anchoring
	Environmental	Adoption of agroecological principles	→ Selection of local varieties adapted to climatic conditions → Crop diversification and livestock integration → Soil and water conservation
		Adoption of circular economy principles	→ Valorization of by-products → Recycling and sustainable waste management → Use of renewable energy
		Water productivity	→ Efficiency of water supply management → Water demand management
	Economic	Income levels	→ Income ranges → Revenues exceeded expenses
		Savings	→ Savings
		Income stabilization	→ Income stabilization
		Diversification (value chain and added value)	→ Diversification (value chain and added value)
		Income security	→ Security of supply sources and market access → Insurance coverage

Figure 2. Diagram of SUSTIN-OLIVA criteria and indicators.

The questionnaire implemented in the SUSTIN-OLIVA application fully reflects the three tables presented in Appendix A (Tables A1–A3), which provide the indicators, their definitions, and the corresponding scoring criteria. To further document the structure of the questionnaire and its integration into the digital application, representative screenshots of the tablet-based questionnaire are provided in Appendix B. SUSTIN-OLIVA adopts an explicitly integrative perspective in which the environmental, economic, and socio-territorial dimensions are considered jointly and assigned near-equal weights of 33, 33, and 34 points, respectively, yielding a total score of 100 points. This weighting reflects the underlying premise that overall sustainability should result from a balanced consideration of the three dimensions rather than from the predominance of any single dimension. Such balance is consistent with the core objective of agroecological transition, which seeks to simultaneously reconcile environmental integrity, economic viability, and socio-territorial sustainability.

As with most composite approaches to agricultural sustainability assessment, the construction of such a framework necessarily involves methodological choices regarding the selection of indicators, the definition of assessment criteria, and the weighting of dimen-

sions. Consequently, a degree of methodological subjectivity cannot be entirely excluded, despite efforts to ground the framework in established methodological principles, empirical evidence, multidisciplinary expertise, and field-based experimentation. In SUSTIN-OLIVA, these methodological choices were addressed through a transparent and evidence-informed design process, while adapting the assessment framework to the specific characteristics of Tunisian olive farming systems.

2.3.2. Digitalization of the SUSTIN-OLIVA Application: Development Environment and Technological Framework

The development of SUSTIN-OLIVA digital application was motivated by the practical limitations associated with conventional paper-based sustainability assessment workflows. In such approaches, data collected in the field must generally be manually transferred, checked, processed, and subsequently used to calculate sustainability indicators, resulting in additional processing time and potential risks of transcription and data-entry errors. SUSTIN-OLIVA was therefore designed to integrate data collection, indicator calculation, data processing, and result generation within a single digital workflow. This enables sustainability results to be generated directly during or immediately after data collection, considerably reducing the time required between fieldwork and data availability for analysis. The integrated workflow also improves data standardization and facilitates the comparison, verification, and export of results across farms.

To support these functions, SUSTIN-OLIVA was implemented within a fully digital environment designed to provide scalability, interoperability, and operational efficiency for sustainability assessment in olive farming systems. The application relies on a modern cross-platform architecture that enables the deployment of a unified system across mobile and web interfaces, while integrating the different stages of the assessment process within a single operational environment.

At the core of the application, the Flutter framework was used as the main software development kit (SDK) version 3.29.0. Flutter enables the development of natively compiled applications from a single codebase, supporting deployment across Android, iOS, and web platforms. Its rendering architecture, based on the Skia graphics engine, provides high-performance and consistent user interfaces across devices. This choice was motivated by the need for a portable and efficient tool suitable for field-based sustainability assessment under heterogeneous operational conditions.

The backend system is based on Supabase, an open-source backend-as-a-service platform built on PostgreSQL. It provides integrated functionalities for database management, authentication, and real-time data synchronization. This architecture enables the structured storage of sustainability indicators and secure API-based access to data, reducing backend development complexity while ensuring scalability and data integrity.

Development was conducted using Visual Studio Code (1.109) and Android Studio (2025.3.1), which together support cross-platform software engineering workflows. VS Code offers extensibility and multi-language support, while Android Studio provides dedicated tools for Android deployment, including SDK management and Gradle-based build automation.

State management was implemented using Cubit, a lightweight state management solution from the Bloc architecture, which enforces the separation between business logic and presentation layers. This design improves code modularity, maintainability, and testability, which are essential for iterative development of decision-support tools [45]. Version control was managed through Git (2.49) and GitHub (Cloud Platform), enabling structured code tracking and collaborative development in a distributed environment [46]. This facilitates reproducibility, transparency, and controlled versioning of the application development process.

Testing was performed using Android and iOS emulators to evaluate interface responsiveness and functional behavior across device configurations. In addition, the Supabase web console (accessed via Google Chrome) was used for database configuration, authentication management, and Row-Level Security policies implementation. Overall, the proposed architecture integrates modern cross-platform development tools with scalable backend services, providing a robust and flexible decision-support system for sustainability assessment in agricultural systems. This digitalization process is summarized in the following flowchart (Figure 3).

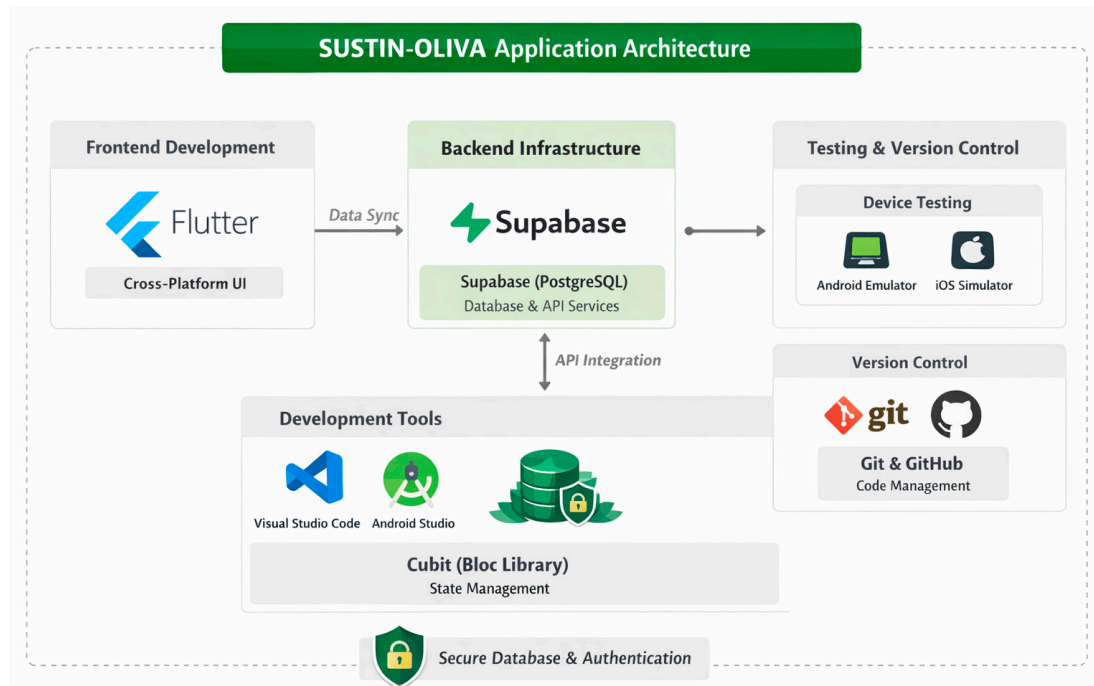


Figure 3. Flowchart of the SUSTIN-OLIVA Digital Application Architecture.

2.3.3. Data Processing and PCA Diagnostics

Principal Component Analysis (PCA) is a well-established statistical technique for analyzing multidimensional datasets. Originally introduced by Karl Pearson [47] and later formalized by [48], it reduces a large set of variables into a smaller number of principal components—linear combinations that maximize explained variance. Widely applied across social, economic, and environmental sciences, PCA facilitates the identification of latent structures, correlations, and underlying relationships within complex systems. In agronomy and rural development, it is commonly used to characterize farming systems, examine agricultural practices, and explore relationships among variables within integrated sustainability assessments. Its key advantage lies in revealing the internal structure of complex data while retaining most of the original information, thereby improving the interpretation of multidimensional patterns [40,49].

In this study, PCA was employed to examine the structure of the sustainability indicator system within olive farming systems undergoing agroecological transition. The analysis focused on the relationships among environmental, economic, and socio-territorial indicators and their contribution to the overall organization of sustainability-related variables at the farm level. Particular attention was given to complementarities, divergences, and potential trade-offs among sustainability criteria, as well as to indicators showing limited adoption or implementation among the surveyed farms. The resulting patterns were used to identify areas that may warrant greater attention from policymakers, advisors, and other stakeholders seeking to strengthen sustainability and support agroecological transition.

The PCA was thus used to complement the sustainability assessment by providing an empirical representation of the relationships among indicators, rather than to validate the framework or establish the statistical significance of individual indicators [50–52].

To explore the interrelationships among sustainability indicators and identify the primary gradients of farm performance, Principal Component Analysis (PCA) was performed independently for each dimension. Prior to analysis, variables were standardized (z-score normalization) to eliminate scale effects. Given the exploratory nature of this study ($N = 61$), PCA was selected as a descriptive exploratory technique rather than a confirmatory latent variable model. Consequently, component stability was evaluated using Anderson's 95% confidence intervals for eigenvalues rather than inferential sampling metrics (such as KMO). Component retention was based on the Kaiser criterion ($\lambda \geq 1.0$), combined with the cumulative variance explained by the primary factorial plane ($F1 \times F2$). All multivariate analyses were executed using SPAD-DECISIA software (version 5.5).

3. Results

3.1. Overview on SUSTIN-OLIVA Digital Application

The SUSTIN-OLIVA application includes several interconnected interfaces. The first interface is dedicated to user identification and is typically used by technicians or researchers responsible for data collection from farmers. This interface is secured through password authentication, ensuring a protected working environment for both decision-makers and farmers, thereby facilitating confidence and ease during the data collection process. The second interface provides essential project identification information, including the project owner's name, the project title, geographic location, total area, and main cropping systems. The project assessment interface is structured into three sub-interfaces corresponding to the three sustainability dimensions. Finally, a results interface summarizes the overall findings in a clear and user-friendly report intended for decision-makers. More detailed outputs are also generated in Excel format, presenting a comprehensive decision matrix that can be further analyzed and used for advanced interpretation. These interfaces are summarized in Figure 4.

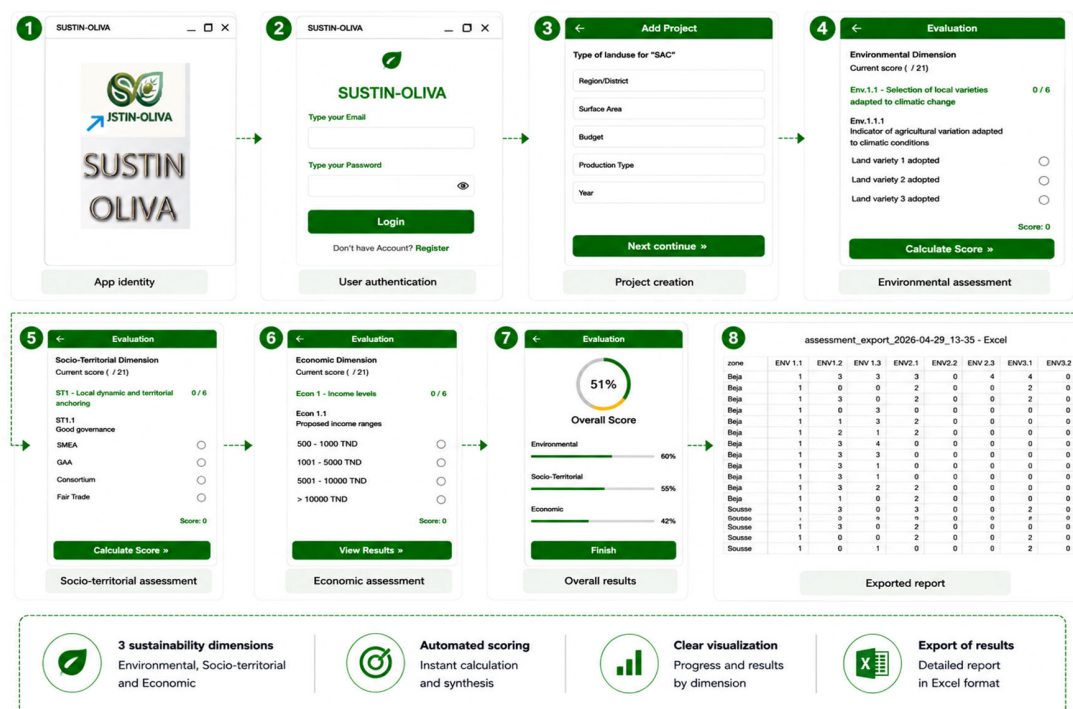


Figure 4. SUSTIN-OLIVA—Overview of the Application Interfaces.

3.2. SUSTIN-OLIVA Implementation: Sustainability Indicators and Strategic Insights

Matrix generated by the SUSTIN-OLIVA application was used to examine the selected sustainability indicators and their corresponding dimensions using real-world data. The analysis focuses on the contribution of the selected indicators to the three sustainability dimensions, providing an empirical basis for identifying the main sustainability strengths and weaknesses captured by the framework. At this level, the results can support the development of strategic measures at the territorial scale to address weaknesses associated with the limited achievement of specific sustainability indicators.

Overall Sustainability

At the outset of this analysis, we aimed to assess the contribution of the three sustainability dimensions—economic, socio-territorial, and environmental—to the overall sustainability of olive-growing systems undergoing ecological transition. The analysis therefore seeks to examine how these three complementary dimensions contribute to the overall sustainability framework and to identify their respective roles in shaping sustainability performance (Figure 5).

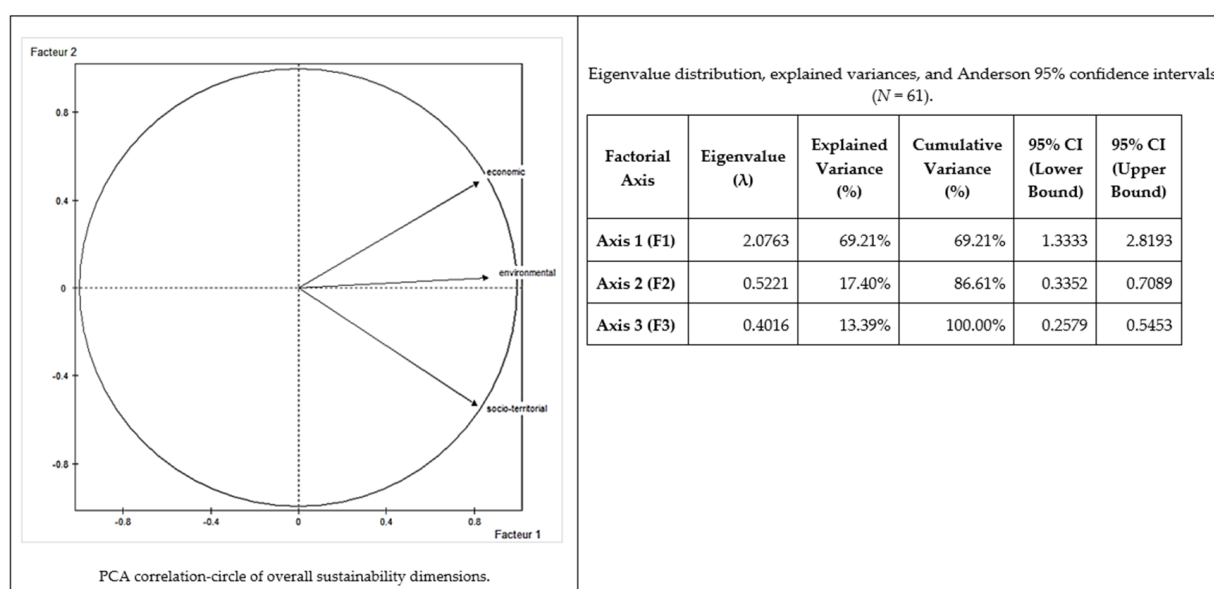


Figure 5. PCA overall sustainability dimensions results.

The analysis of the correlation matrix indicates that the three sustainability dimensions exhibit positive, moderate-to-strong inter-variable correlations, all highly significant at the $\alpha = 0.001$ level (t -test values > 1.96 , $N = 61$): between environmental and economic dimensions ($r = 0.58$, $t = 5.12$), between socio-territorial and environmental dimensions ($r = 0.56$, $t = 4.93$), and between socio-territorial and economic dimensions ($r = 0.48$, $t = 4.07$). This tri-variate synergy confirms overall structural coherence across the surveyed olive farms. These positive associations indicate that the three pillars tend to evolve in the same direction across the surveyed farms, providing initial evidence of structural coherence within the sustainability assessment framework.

The global PCA conducted on these three synthetic dimensions confirms this structure. According to Kaiser's criterion $\lambda > 1.0$, the first factorial axis $\lambda_1 = 2.0763$ alone accounts for nearly 70% of total variance (Table 1). Evaluation of the 95% Anderson confidence intervals shows clear statistical separation between the first and second axes ([1.3333; 2.8193] vs. [0.3352; 0.7089]), confirming the high statistical stability of the primary factor.

Table 1. PCA-Coding indicators.

Socio-Territorial Dimension	
Code Indicator	
C1	Good governance
C2	Valorization of local know-how
C3	Involvement in community life and openness to the surrounding environment
C4	Valorization through a quality label
C5	Multifunctionality of agriculture
C6	Short supply chains
C7	Corporate Social Responsibility (CSR)
C8	Farmers' quality of life
C9	Proportion of women among workers
C10	Proportion of young people (<40 years old) among workers (Youth)
C11	Formalization and decency of employment
C12	Capacity building, training related to the ecological transition, and/or recruitment of qualified staff
C13	Territorial embeddedness
Economic Dimension	
Code Indicator	
V1	Income range
V2	Revenues exceeding expenses
V3	Savings
V4	Income stabilization
V5	Diversification
V6	Security of supply sources and market access
V7	Insurance coverage
Environmental Dimension	
Code Indicator	
E1	Selection of local varieties adapted to climatic conditions
E2	Crop diversification and livestock integration
E3	Soil and water conservation
E4	Valorization of by-products
E5	Recycling and sustainable waste management
E6	Renewable energy
E7	Water use efficiency or control over water supply
E8	Demand-side management based on optimized water needs across the entire farm

Nevertheless, retaining the F1 * F2 factorial plane was selected to achieve 86.61% cumulative variance and capture underlying secondary trade-offs.

Axis F1 (69.21% of variance)—Global sustainability Gradient: Axis F1 exhibits high correlations across all three pillars: $r(C2, F1) = 0.86$ (Environmental), $r(C3, F1) = 0.82$ (Economic), and $r(C1, F1) = 0.81$ (Socio-territorial). It can therefore be interpreted as a global sustainability performance gradient, reflecting a size/overall performance ef-

fect: farms scoring high on Axis 1 simultaneously display strong performance across all three dimensions, demonstrating structural complementarity during agroecological transition. Rather than indicating that the three dimensions are interchangeable, this result highlights their complementary contribution to overall sustainability in agroecological transition context.

Axis F2 (17.40% of variance)—Economic vs. Socio-Territorial Trade-off: Axis F2 opposes economically driven profiles ($r(C3, F2) = +0.48$) against socio-territorially anchored profiles ($r(C1, F2) = -0.54$), while the environmental component remains neutral ($r(C2, F2) = 0.04$). This axis highlights a typology of strategic trade-offs at comparable overall sustainability levels: certain farms prioritize immediate economic returns, whereas others place greater emphasis on social and territorial integration. This secondary opposition does not contradict the overall coherence identified along F1; rather, it suggests that farms may share a broadly similar global sustainability orientation while differing in the relative emphasis placed on economic performance and socio-territorial embeddedness.

The vector projections in Figure 5 confirm the initial hypothesis of a coherent three-pillar sustainability structure, while revealing strategic management trade-offs between economic performance and socio-territorial embeddedness.

In conclusion, although the socio-territorial dimension appears to be more demanding and restrictive in terms of sustainability compared to the economic and environmental dimensions, it remains a fundamental component in the overall definition of sustainability—thus confirming the initial hypothesis.

3.3. Internal Exploration of Indicators Through PCA

PCA was conducted separately for the economic, socio-territorial, and environmental groups of indicators using the decisional matrix generated by the SUSTIN-OLIVA application. This exploratory analysis examined the internal structure of each sustainability dimension and the contribution of individual indicators to its overall performance. The results highlight both the indicators contributing most strongly to each dimension and those associated with weaker performance, thereby identifying areas where strategic interventions can address weaknesses and reinforce existing strengths at the territorial level.

Table 1 provides a complete list of the indicators and their corresponding codes used in the PCA analysis.

3.3.1. Socio-Territorial Dimension Indicators' Test

To examine the interactions within the socio-territorial dimension, all 13 variables listed in Table 1 were subjected to Principal Component Analysis (PCA) across the 61 farm units. The analysis showed that 10 variables contributed meaningfully to the principal components, whereas the remaining three variables exhibited negligible contributions. The corresponding PCA results are presented in Table 2.

Although four axes exceed Kaiser's threshold ($\lambda > 1.0$), the first two components; explaining 70.05% of cumulative variance (F1: 53.52%, $\lambda_1 = 5.3522$; F2: 16.53%, $\lambda_2 = 1.6532$); were retained to ensure a legible bidimensional spatial projection. Anderson's 95% confidence intervals confirm the statistical separation of both main factors ([3.4370; 7.2675] vs. [1.0616; 2.2448]).

Table 2. Socio-territorial indicators PCA factor loadings and eigenvalues (N = 61).

Code	Indicator	F1 (53.5%)	F2 (16.5%)
C1	Good governance	0.05	0.41
C2/C7/C10	Know-how/CSR/Youth	0.96	−0.26
C3	Community involvement	0.86	−0.06
C4	Quality labeling	0.69	−0.07
C5	Multifunctionality	0.66	−0.29
C6	Short supply chains	0.6	0.73
C9	Share of women	0.29	0.47
C13	Territorial embeddedness	0.7	0.66

Factor Loadings Summary (N = 61):

Axis F1 $\lambda_1 = 5.35$; 53.52% Var.—Global Engagement Gradient: C2/C7/C10 ($r = 0.96$), C3 ($r = 0.86$), C13 ($r = 0.70$), C4 ($r = 0.69$), C5 ($r = 0.66$), C6 ($r = 0.60$).

Axis F2 $\lambda_2 = 1.65$; 16.53% Var.—Proximity & Inclusion: C6 ($r = 0.73$), C13 ($r = 0.66$), C9 ($r = 0.47$), C1 ($r = 0.41$).

Structuring of Axis F1 (53.52% of variance)—Overall Socio-Territorial Engagement Gradient: Axis F1 reflects a primary size/intensity effect. It is strongly correlated with local engagement practices: Valorization of local know-how (C2, $r = 0.96$), Corporate Social Responsibility (C7, $r = 0.96$), and Youth integration (C10, $r = 0.96$) display near-perfect projections on this component. It is further supported by Community involvement (C3, $r = 0.86$), Territorial embeddedness (C13, $r = 0.70$), Quality labeling (C4, $r = 0.69$), and Multifunctionality (C5, $r = 0.66$). This factor contrasts highly structured, community-engaged farms against less integrated units.

Structuring of Axis F2 (16.53% of variance)—Short Supply Chains and Proximity: Axis F2 is specifically structured by Short supply chains (C6, $r = 0.73$) and Territorial embeddedness (C13, $r = 0.66$), which exhibit strong collinearity ($r(C6, C13) = 0.98$, $t = 17.78$). Proportion of women workers (C9, $r = 0.47$) and Good governance (C1, $r = 0.41$) also load positively on F2, isolating a marketing relocation and local inclusion strategy.

Secondary Axes and Variable Preprocessing: Good governance (C1) exhibits an orthogonal relationship with F1 ($r = 0.05$) and is primarily captured by Axis F3 ($\lambda_3 = 1.0625$, 10.63% of variance, $r = -0.84$), demonstrating that governance acts as an independent decision-making dimension. Indicators C8, C11, and C12 have weak contributions due to near-zero variance across the sample. This reflects their weak correlation with the two main axes and thus a negligible contribution to the structuring of the factorial space.

3.3.2. Economic Dimension Indicators' Test

The economic sustainability of olive farming systems was evaluated across 61 farm units using 7 proposed continuous indicators (Table 2). All 7 indicators were active in the factorial analysis, capturing short-term financial viability, risk management, and long-term capital preservation (Table 3).

Principal Component Analysis (PCA) extracted three components with eigenvalues exceeding 1.0 (Kaiser criterion), collectively explaining 67.52% of total cumulative variance. The primary factorial plane (F1 * F2) accounts for 53.13% of total variance (F1: 33.11%, $\lambda_1 = 2.3179$; F2: 20.02%, $\lambda_2 = 1.4012$). Anderson's 95% Laplacian confidence intervals validate the statistical separation and independence of F1 ([1.4885; 3.1474]) and F2 ([0.8998; 1.9026]).

Table 3. Economic indicators PCA factor loadings and eigenvalues (N = 61).

Code	Indicators	F1 (33.11%)	F2 (20.02%)	F3 (14.39%)
V1	Income range	−0.67	0.09	−0.31
V2	Revenues exceeding expenses	−0.78	0.18	−0.2
V3	Savings	−0.12	−0.63	0.29
V4	Income stabilization	0.7	−0.52	0.02
V5	Diversification	−0.62	−0.46	0.11
V6	Security of supply sources & market access	−0.18	−0.68	−0.58
V7	Insurance coverage	−0.58	−0.13	0.66

Axis F1 (33.11% of variance)—Viability and Diversification Gradient: Axis F1 reflects a core gradient of financial capacity and farm-level diversification. All primary contributors project onto the negative pole of F1: Revenues exceeding expenses (V2, $r = -0.78$), Income range (V1, $r = -0.67$), Diversification (V5, $r = -0.62$), and Insurance coverage (V7, $r = -0.58$). Conversely, Income stabilization (V4, $r = +0.70$) projects onto the positive pole. Farms positioned at the negative extreme of F1 display high structural economic resilience, higher income levels, and risk-mitigation strategies through diversification and insurance.

Axis F2 (20.02% of variance)—Supply Security and Capital Preservation: Axis F2 captures financial planning and input/market stability. It is structured along the negative pole by Security of supply sources and market access (V6, $r = -0.68$), Savings (V3, $r = -0.63$), Income stabilization (V4, $r = -0.52$), and Diversification (V5, $r = -0.46$). Negative scores on F2 represent forward-looking economic strategies relying on input security, market stability, and financial reserves to buffer external market shocks.

Secondary Axis F3 (14.39% of variance): Axis F3 ($\lambda_3 = 1.0075$) isolates formal risk hedging from supply integration, driven by Insurance coverage (V7, $r = +0.66$) opposed to Security of supply sources (V6, $r = -0.58$).

3.3.3. Environmental Dimension Indicators' Test

Environmental sustainability represents a fundamental pillar of the resilience of olive farming systems, particularly in the context of climate change and increasing pressure on natural resources. Eight indicators were initially considered to assess this dimension, covering sustainable resource management practices, input efficiency, biological integration, and the capacity of farms to adapt to local environmental conditions. The indicators and their corresponding codes are presented in Table 1.

Environmental sustainability was assessed across 61 farm units (Table 4). Among the eight indicators considered, Recycling and waste management (E5) and Renewable energy (E6) showed very low levels of adoption across the surveyed farms, resulting in limited variability and consequently a weak contribution to the factorial structure. Their low contribution should therefore be interpreted primarily as a reflection of the current state of environmental practices in the study area, rather than as an indication of low conceptual relevance to environmental sustainability or agroecological transition. In contrast, the other indicators displayed greater variability across farms and therefore contributed more substantially to differentiating environmental sustainability profiles.

Table 4. Environmental indicators PCA factor loadings (N = 61).

Code	Indicator	F1 (39.8%)	F2 (20.0%)
E1	Selection of local adapted varieties	0.16	−0.54
E2	Crop diversification & livestock integration	0.58	−0.36
E3	Soil and water conservation	0.94	0.18
E4	Valorization of by-products	0.2	0.79
E7	Water use efficiency & supply control	0.47	−0.33
E8	Demand-side water management	0.94	0.12

Following the PCA, E5 (recycling and sustainable waste management) and E6 (renewable energy) showed weak contributions to the first two principal components, reflecting low adoption in current farming practices rather than low relevance. Their limited statistical weight is mainly due to implementation constraints, not their intrinsic importance. On the contrary, these indicators remain key levers for agroecological transition and circular economy development in olive systems, requiring targeted policy and technical support to enhance their future adoption.

The Principal Component Analysis (PCA) extracted three factorial axes with eigenvalues exceeding 1.0 (Kaiser criterion), accounting for 76.46% of total cumulative variance. For bidimensional display, the first two axes—explaining 59.76% of cumulative variance (F1: 39.81%, $\lambda_1 = 2.3884$; F2: 19.95%, $\lambda_2 = 1.1970$)—were retained. Anderson’s 95% confidence intervals validate the statistical separation and independence of F1 ([1.5337; 3.2430]) and F2 ([0.7687; 1.6254]).

Axis F1 (39.81% of variance)—Soil Conservation and Water Efficiency Gradient: Axis F1 is strongly structured by resource conservation practices. It shows dominant positive correlations with Soil and water conservation (E3, $r = +0.94$) and Demand-side water management (E8, $r = +0.94$), which exhibit high mutual collinearity ($r = 0.95$). These are complemented by Crop diversification and livestock integration (E2, $r = +0.58$) and Water use efficiency (E7, $r = +0.47$). F1 represents a gradient of technical resource efficiency and soil protection practices.

Axis F2 (19.95% of variance)—Circular Economy vs. Varietal Adaptation: Axis F2 reflects trade-offs in farm-level biological integration. It is heavily defined by Valorization of by-products (E4, $r = +0.79$) on the positive pole, opposed to Selection of local adapted varieties (E1, $r = -0.54$) on the negative pole. Farms scoring high on F2 prioritize circular economy strategies (e.g., pomace/wastewater valorization), whereas negative scores reflect traditional dependence on local landraces.

Secondary Component (Axis F3): Axis F3 ($\lambda_3 = 1.0023$, 16.71% of variance) is defined by Selection of local varieties (E1, $r = -0.73$) and Water use efficiency (7, $r = +0.57$), isolating varietal choice from technical irrigation control.

3.3.4. Holistic Exploration of Sustainability and Strategic Implications

Indicator-Level Contributions and Strategic Implications

The application of the SUSTIN-OLIVA digital method to the case study provided an empirical basis for examining how the selected indicators contribute to the three dimensions of sustainability in olive farming systems undergoing agroecological transition. Rather than interpreting the indicators independently, the analysis considered their relative contribution within the overall sustainability structure captured by the Principal Component Analysis (PCA). This approach makes it possible to distinguish indicators that are more strongly expressed in the observed sustainability structure from those showing comparatively

lower contributions, thereby providing context-specific insights into potential areas for strategic attention.

The results indicate that the contribution of individual indicators varies across the three sustainability dimensions. This variability does not necessarily reflect the intrinsic importance of an indicator, but rather its level of variability and its capacity to discriminate among the farms included in the case study. Consequently, indicators showing lower contributions should not be interpreted as being less important for sustainability; instead, they may identify aspects that are less differentiated across farms or that require stronger implementation, monitoring, or policy support.

For the socio-territorial dimension, the PCA revealed a differentiation between indicators showing stronger contributions to the observed sustainability structure, such as Good Governance, Valorization of Local Know-how, Community Involvement and Openness to the Surrounding Environment, and Valorization through Short Supply Chains, and indicators showing comparatively lower contributions, including Farmers' Quality of Life, Formalization and Decency of Employment, and Capacity Building. The lower contribution of these indicators should not be interpreted as indicating lower importance for sustainability. Rather, it may reflect limited variability among the surveyed farms, the structural nature of these dimensions, or the difficulty of capturing them quantitatively within predominantly smallholder and family-based farming systems. From a strategic perspective, these results highlight areas where stronger institutional support, social organization, employment conditions, knowledge development, and attention to farmers' well-being could contribute to strengthening the socio-territorial dimension of agroecological transition.

In the environmental dimension, Recycling and Sustainable Waste Management and Renewable Energy showed comparatively lower contributions to the observed sustainability structure. These results may partly reflect limited variability in the adoption of these practices among the surveyed farms, as well as the relatively low prevalence of formalized recycling systems and renewable-energy technologies. Their lower statistical contribution should therefore not be interpreted as evidence of limited environmental relevance. On the contrary, these areas represent potential entry points for targeted interventions aimed at strengthening resource recovery, waste management, energy efficiency, and the gradual adoption of appropriate renewable-energy solutions. At the same time, the stronger contribution of other environmental indicators points to existing sustainability practices that could be consolidated and further supported through targeted interventions.

In contrast, the economic dimension showed relatively strong contributions across its indicators, reflecting substantial differentiation in the economic conditions and strategies of the surveyed farms. Indicators related to income, profitability, savings, income stabilization, diversification, supply security, and market access contributed to the sustainability structure captured by the PCA. This pattern underlines the central role of economic viability in the capacity of farms to engage in and sustain agroecological transition. From a strategic perspective, these results suggest that maintaining economic resilience while addressing farm-specific economic constraints is essential for supporting longer-term sustainability transitions.

Importantly, SUSTIN-OLIVA is designed as a multidimensional and flexible framework that can be applied across diverse production contexts. The results therefore need to be interpreted at two complementary levels. At the indicator level, the PCA helps identify areas that are more strongly expressed in the observed sustainability structure and areas where further attention may be warranted. At the farm level, the combination of sustainability indicators reveals differentiated profiles resulting from distinct configurations of environmental, socio-territorial, and economic characteristics. These two levels of analysis are complementary: the indicator-level assessment helps identify what aspects of

sustainability deserve attention, whereas the farm-level analysis helps identify where and for whom targeted strategies may be most relevant.

Overall, the results provide a context-specific exploration of the sustainability structure captured by SUSTIN-OLIVA and highlight differentiated contributions of the indicators across the three sustainability dimensions. Among the 28 indicators initially considered, 23 displayed sufficient contributions to the factorial structure examined through the PCA, whereas five indicators showed comparatively limited contributions to the first two principal components (Table 5). These lower contributions should not be interpreted as evidence that the corresponding sustainability aspects are irrelevant. Rather, they indicate that these indicators contributed less to differentiating the farms within the specific case study and may therefore warrant further attention in terms of implementation, monitoring, data collection, or targeted policy support.

Table 5. SUSTIN-OLIVA indicators according to their relative contribution to the factorial structure observed in the case study.

Dimensions	Criteria	SUSTIN-OLIVA Indicators	Indicators with Lower Contributions	Indicators with Stronger Contribution
Socio-territorial	Local dynamic and territorial anchorage	Good governance		X
		Valorization of local know-how		X
		Involvement in community life and openness to the surrounding environment		X
		Valorization through a quality label		X
		Multifunctionality of agriculture		X
	Valorization through short supply chains	Short supply chains		X
	Corporate Social Responsibility			X
	Farmers' quality of life		X	
	Job creation and retention/Inclusion of women, youth, and decent work	Proportion of women among workers		X
		Proportion of young people (<40 years old) among workers		X
		Formalization and decency of employment	X	
		Capacity building, training related to the ecological transition, and/or recruitment of qualified staff	X	
	Territorial embeddedness			X
Environmental	Adoption of agroecological principles	Selection of local varieties adapted to climatic conditions		X
		Crop diversification and livestock integration		X
		Soil and water conservation		X
	Adoption of circular economy principles	Valorization of by-products		X
		Recycling and sustainable waste management	X	
		Renewable energy	X	
	Efficiency in water use in the production process (Water productivity)	Water use efficiency or control over water supply		X
		Demand-side management based on optimized water needs across		X

Table 5. Cont.

Dimensions	Criteria	SUSTIN-OLIVA Indicators	Indicators with Lower Contributions	Indicators with Stronger Contribution
Economic	Securing supply	Income range		X
		Revenues exceeding expenses		X
		Savings		X
		Income stabilization		X
		Diversification		X
		Security of supply sources and market access		X
		Insurance coverage		X
Total indicators		28	5	23

Farm-Level Sustainability Profiles and Targeted Strategies

Building on the indicator-level analysis presented above, the farm-level assessment provides a complementary perspective on how sustainability is expressed across individual holdings. While the PCA of the indicators identifies which sustainability attributes are more strongly associated with the observed factorial structure, the distribution of indicator scores across farms makes it possible to examine how these attributes combine within individual farm profiles.

The distribution of the SUSTIN-OLIVA indicators across the 61 farms illustrates substantial heterogeneity in sustainability profiles within the case study (Figure 6). The stacked representation highlights differences in the overall configuration of sustainability-related attributes among farms, both within and between the two study areas, Béja and Sousse–Monastir. Some farms display relatively balanced profiles across the assessed indicators, whereas others show more pronounced differences in specific sustainability components. This variability provides an empirical basis for examining farm-level differentiation and for identifying whether sustainability-oriented strategies may need to be differentiated according to farm profiles.

To further explore these differentiated farm profiles, a Principal Component Analysis was performed using the sustainability indicators retained for the case study. The factorial projection of the 61 farms onto the first two principal components revealed substantial differentiation among farm profiles (Figure 7). Most farms were concentrated around the centre of the factorial space, whereas a smaller number occupied more distinct positions. The analysis identified three groups of farms, reflecting different combinations of environmental, socio-territorial, and economic sustainability characteristics.

The differentiated position of these farms should not necessarily be interpreted as indicating higher or lower overall sustainability. Rather, it reflects distinctive combinations of sustainability attributes within the factorial space. In particular, the reference farm (Farm 01) occupies an extreme positive position along F1, while Farm 06 is also clearly differentiated. The position of the reference farm is consistent with its role as a benchmark case within the SUSTIN-OLIVA framework and reflects a combination of characteristics that differs substantially from those observed in most of the sampled farms.

These differentiated farm profiles have important implications for the strategic use of SUSTIN-OLIVA. The results suggest that sustainability-oriented interventions should not necessarily follow a uniform approach across all farms. For farms belonging to the predominant group, strategies could give particular attention to sustainability attributes that showed comparatively lower contributions in the case study, particularly those related

to social organization, employment conditions, capacity building, resource efficiency, recycling, and renewable energy. For farms occupying more differentiated positions in the factorial space, the objective may instead be to consolidate existing strengths and identify practices that could be adapted, where appropriate, to other farm contexts.

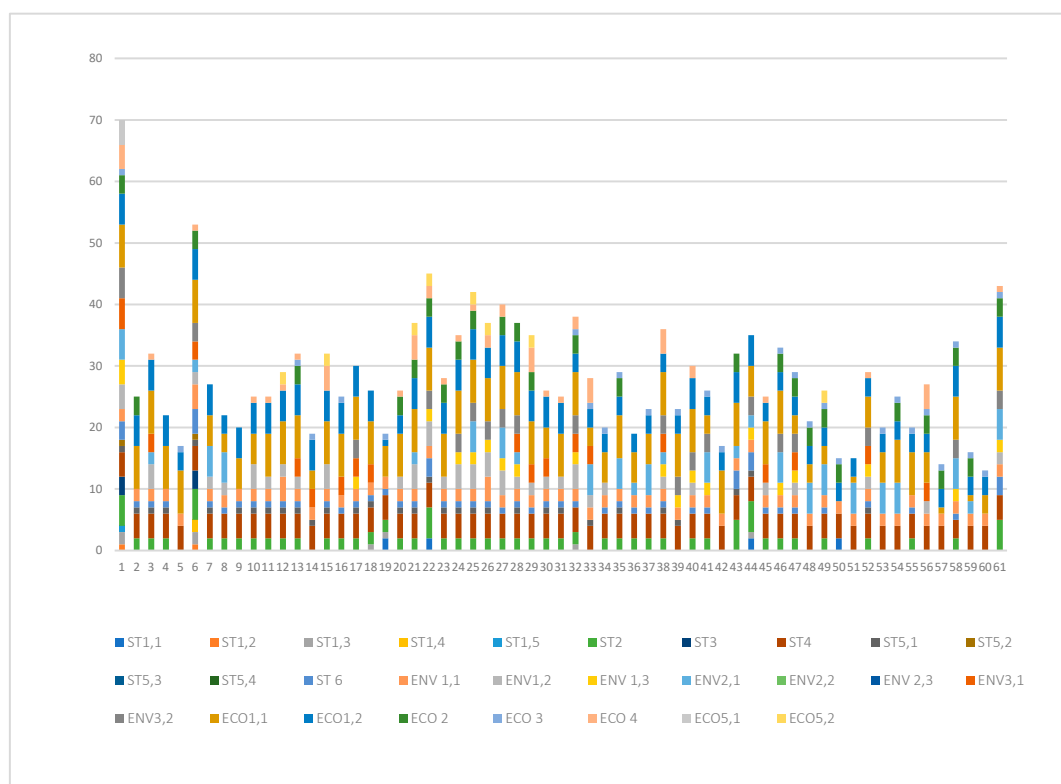


Figure 6. Sustainability indicators among the 61 farms. Farms 1 to 31: Beja agroecological region; Farms 32 to 61: Sousse Monastir agroecological region; Farm 1 is the reference farm.

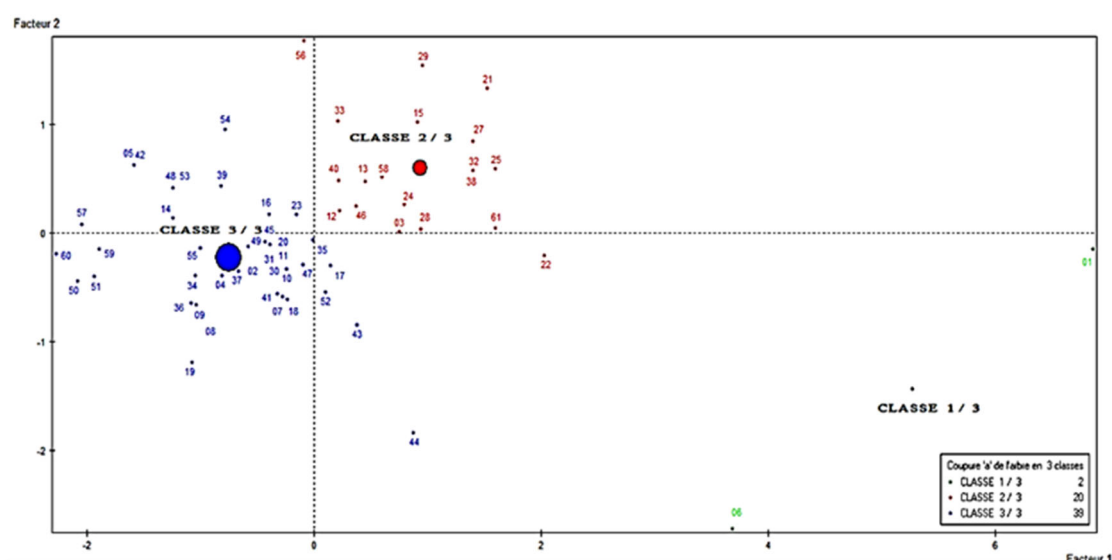


Figure 7. PCA overall sustainability indicators Farms typology.

The reference farm should therefore be interpreted not as a statistically representative farm, but as a benchmark or illustrative case within the SUSTIN-OLIVA framework. Its distinct position in the factorial space highlights a particular combination of sustainability attributes and provides a useful basis for identifying practices that may offer transferable

lessons. However, any transfer of such practices should take into account differences in farm structure, production systems, resource availability, and local conditions.

Taken together, the indicator- and farm-level analyses provide two complementary forms of information. The indicator-level analysis identifies the sustainability attributes that contribute most or least to the observed factorial structure, while the farm-level analysis reveals how these attributes are combined across individual holdings. This distinction is important for strategic planning, as it suggests that territorial policies may prioritize specific sustainability areas requiring further attention, whereas farm-level interventions should be adapted to the characteristics and constraints of different farm profiles.

4. Discussion

The results of this study provide insights into the use of a digitalized, indicator-based approach to examining sustainability in Tunisian olive farming systems undergoing agroecological transition. Consistent with the conceptual and methodological foundations of the SUSTIN-OLIVA framework, PCA was used as an exploratory multivariate technique to examine the internal structure of the indicator system and the relationships among indicators across the three sustainability dimensions. The analysis provides information on how individual indicators are associated with the observed factorial structure and helps identify indicators with relatively stronger or weaker contributions within the study sample. Given the cross-sectional and exploratory nature of the analysis, these patterns should be interpreted as associations and structural relationships rather than as evidence of causal effects or predictive relationships.

The PCA results are broadly consistent with previous applications of multivariate approaches to farm sustainability assessment. Gaviglio et al. (2017), for instance, used PCA to explore relationships among environmental, social, and economic sustainability indicators and showed that the resulting components could reveal patterns of farm sustainability beyond the initial classification of indicators into predefined pillars [52]. Similarly, Vanino et al. (2022), although using a fuzzy-logic rather than PCA-based approach, demonstrated that agro-environmental indicators can discriminate among diversified cropping systems and Mediterranean production contexts, highlighting the importance of context-specific indicators in sustainability assessment [53]. These studies support the use of multivariate approaches to investigate relationships among sustainability indicators rather than treating the different dimensions as completely independent analytical domains.

The observed factorial structure indicates substantial interconnections among the economic, environmental, and socio-territorial dimensions. Farms characterized by stronger economic performance also tended to display more favorable environmental management practices and greater socio-territorial engagement. This association suggests that the different dimensions may interact within the sustainability profiles of the farms considered, but it does not imply that stronger economic performance directly causes improvements in environmental or socio-territorial performance. Such convergence supports the view that sustainability in olive farming cannot be adequately addressed through isolated improvements in individual sectors or practices, but requires integrated strategies that consider productivity, resource efficiency, resilience, and territorial cohesion simultaneously [54–56]. In this respect, the findings are consistent with the systems perspective underpinning the SUSTIN-OLIVA framework and its decision-support orientation.

At the same time, the PCA revealed contrasting patterns that may reflect potential trade-offs among sustainability priorities, particularly between economic competitiveness and socio-territorial anchoring. The observed configuration suggests that some economically oriented farms place greater emphasis on income stability and market integration, whereas other farms with stronger territorial and traditional-knowledge dimensions may

exhibit different economic profiles. These patterns should be interpreted cautiously as associations within the sampled farms rather than as evidence that one sustainability dimension determines another. Similar tensions have been reported in Mediterranean and Latin American agroecosystems, where market integration, economic constraints, and institutional conditions can influence the pathways followed by agroecological transitions [22,57,58]. The results therefore highlight the importance of adaptive governance mechanisms capable of recognizing potentially competing sustainability priorities rather than assuming that improvements in one dimension will automatically translate into improvements in all others. Digital decision-support systems may contribute to this process by making such multidimensional patterns more visible and easier to monitor [8,59].

From the socio-territorial perspective, the stronger contributions of indicators such as local know-how valorization, multifunctionality, corporate social responsibility (CSR), and territorial embeddedness underline the importance of cultural, organizational, and collective dimensions within olive-based agroecosystems. These dimensions reflect the multifunctional role of agriculture in rural territories, where production activities are closely connected with cultural heritage, local knowledge, social relations, and territorial cohesion [60,61]. These characteristics also illustrate that sustainability is partly shaped by the ways farmers organize their activities, mobilize local knowledge, interact with their communities, and engage with territorial networks. The differentiated farm profiles observed in the PCA suggest that such socio-territorial characteristics can be combined differently across individual holdings [24]. By contrast, the comparatively weaker contributions of indicators related to formal employment, training access, and farmer well-being identify areas that may deserve greater attention in future interventions. Such weaknesses may be particularly relevant in contexts characterized by informal labor arrangements and limited institutional support for capacity building, as reported in studies of agroecological transitions in the Global South [62,63]. Importantly, weaker PCA contributions should not be interpreted as indicating that these issues are intrinsically less important for sustainability; rather, they indicate that they contributed less strongly to the component structure observed in the present sample.

The economic dimension emerged as the most prominent dimension in the observed PCA structure. Indicators related to income stability, diversification, savings capacity, and market or risk security contributed strongly to differentiating the economic sustainability profiles of the sampled farms. Their contribution highlights the importance of economic resilience in the capacity of farms to cope with climatic and market uncertainty and potentially engage in agroecological transition pathways [55,58]. In the Tunisian context, diversification is particularly relevant to farm resilience under increasing climatic variability and market uncertainty [41,44,64]. However, the PCA does not establish that these indicators cause greater adoption of agroecological practices. Rather, their joint contribution suggests that economic resilience constitutes an important component of the sustainability profiles observed in the study. This finding supports the need for transition strategies that do not consider environmental improvements independently from the economic viability of farming systems.

Environmental sustainability was primarily structured around two complementary areas: natural-resource management and by-product valorization. Water-use efficiency, soil conservation, and diversification reflect key aspects of resource management in Mediterranean dryland agroecosystems, where water scarcity, soil degradation, and climatic variability constitute major constraints to long-term agricultural resilience [65,66]. At the same time, practices related to composting and olive-mill-waste recycling illustrate opportunities to increase the circularity of olive production by recovering organic matter and other potentially valuable resources [67,68]. The comparatively weaker contributions of indicators

associated with mechanization, energy efficiency, and waste-management practices suggest that these areas may require additional technical support, awareness, investment, or capacity building. Again, these lower contributions should be interpreted as characteristics of the observed indicator structure rather than as direct measures of the absolute importance of these practices for environmental sustainability.

Beyond the contribution of individual indicators, the farm-level analysis provides an additional perspective on how sustainability attributes are combined within individual holdings. The three farm groups identified through the PCA reflect differentiated combinations of environmental, socio-territorial, and economic characteristics rather than a simple ranking from more to less sustainable farms. This distinction is important for interpreting the results because a farm occupying a differentiated position in the factorial space cannot automatically be considered more or less sustainable overall. Rather, its position indicates a particular configuration of sustainability attributes within the multidimensional structure captured by SUSTIN-OLIVA.

The farm-level differentiation also highlights the importance of considering farmers as heterogeneous actors within agroecological transition processes. Farmers may have different combinations of resources, production strategies, market relationships, knowledge, and territorial engagement, which can influence the way sustainability practices are adopted and combined at farm level [24]. Consequently, a uniform transition strategy may not respond equally to the circumstances of all farms. The differentiated profiles identified in this study therefore provide a basis for considering more targeted approaches to technical support, advisory services, capacity building, and other transition measures.

The reference farm provides a particularly illustrative example of this differentiation. Its distinct position in the factorial space is consistent with its role as a benchmark case within the SUSTIN-OLIVA framework and reflects a combination of sustainability characteristics that differs substantially from those observed in most sampled farms. However, the reference farm should not be interpreted as statistically representative of the wider population of Tunisian olive farms, nor should its position be considered evidence of universally superior sustainability performance. Instead, it provides an illustrative configuration from which potentially transferable practices can be identified and examined in relation to the conditions of other farms.

From a strategic perspective, this distinction between indicator-level and farm-level information is particularly relevant. Indicator-level analysis can identify sustainability areas that contribute relatively strongly or weakly to the observed structure, whereas farm-level analysis shows how these areas are combined differently across individual holdings. The two levels therefore provide complementary information: territorial and sectoral policies can give attention to sustainability areas requiring broader institutional or infrastructural support, while farm-level interventions can be adapted to the specific characteristics, constraints, and capacities of different groups of farmers [24].

Overall, the findings suggest that Tunisian olive farming systems are undergoing a gradual but uneven sustainability transition. Economic resilience appears as a prominent component of the sustainability structure observed in the study sample, while socio-territorial and environmental dimensions remain characterized by heterogeneous patterns across indicators and farms. The differentiated contribution of indicators and the differentiated farm profiles provide a basis for identifying strategic priorities: consolidating areas that already show strong contributions while giving greater attention to sustainability areas characterized by weaker contributions or lower levels of achievement. This distinction is important because a sustainability framework should not only identify strengths but also make visible the areas where additional support, investment, or institutional action may be required. In this respect, SUSTIN-OLIVA provides a structured digital environment

for organizing sustainability indicators, exploring their interrelationships, and translating indicator- and farm-level information into broader strategic considerations.

By integrating sustainability indicators into a digital architecture, the framework contributes to the broader transformation of agricultural assessment systems toward more systematic and data-supported approaches [8,59]. Its methodological logic remains compatible with established sustainability assessment approaches such as MESMIS [22], SAFA [25], and RISE [69], while its main added value lies in the digitalization of the assessment workflow. Rather than introducing a fundamentally new sustainability concept, SUSTIN-OLIVA operationalizes a multidimensional indicator framework within an integrated digital environment. This allows data to be collected, processed, scored, and reported within a single system, thereby improving the consistency and operational efficiency of the assessment process.

The practical value of SUSTIN-OLIVA therefore lies primarily in the integration and digitalization of the assessment workflow rather than in the specific technologies used to develop the application. By combining data collection, automated indicator calculation, and result generation within the same environment, the application reduces the need for subsequent manual data entry, limits potential transcription errors, and reduces the time between field data collection and the availability of assessment results. The possibility of exporting results to Excel further facilitates data checking, analysis, reporting, and comparison across farms. In this respect, SUSTIN-OLIVA contributes to the broader development of integrated digital approaches in agriculture, where the value of digitalization increasingly depends on the ability to connect data collection, farm-level tasks, and decision processes rather than on the adoption of individual technologies in isolation [5,39]. Recent research similarly emphasizes the potential of digitalization to support multiple sustainability dimensions and provide information relevant to managerial and policy decisions, while recognizing that the effective integration of digital functions into coherent farm-level systems remains challenging [5,39].

The digital approach should nevertheless be regarded as complementary to, rather than universally superior to, conventional paper-based assessment. Paper questionnaires may facilitate the recording of contextual observations, qualitative explanations, and assessor comments that can help interpret particular responses or unexpected sustainability patterns. SUSTIN-OLIVA currently provides greater standardization and processing efficiency, while future versions could incorporate dedicated fields for qualitative observations and assessor notes. This complementarity is consistent with the broader literature on sustainability assessment tools, which emphasizes that their usefulness depends not only on measurement and reporting but also on the interpretation and practical use of the resulting information in decision-making processes [6]. At a broader level, standardized digital outputs could facilitate the aggregation and sharing of farm-level information among researchers, advisors, extension services, and other stakeholders, provided that appropriate data-governance and confidentiality mechanisms are maintained. However, evidence from African smallholder contexts indicates that, despite the considerable potential of digital tools, empirical evidence regarding their actual effects on environmental sustainability and climate resilience remains limited [31]. The present study therefore demonstrates the operational value of digitalizing sustainability assessment, while further research is needed to determine whether improved assessment and information availability ultimately translate into changes in farm management and sustainability outcomes.

From an international perspective, the relevance of SUSTIN-OLIVA lies less in the direct replication of its current indicator set than in the possibility of adapting its digital architecture to different farming contexts. Previous sustainability assessment initiatives have demonstrated the need to integrate environmental, economic, and social dimen-

sions while accounting for substantial differences in agroecological conditions, farming practices, and institutional settings [31]. In this respect, the modular structure of SUSTIN-OLIVA provides a potential basis for developing comparable digital assessment applications in other Mediterranean olive-growing regions or agricultural systems in developing-country contexts. Such transfer, however, should not involve the direct application of the Tunisian configuration. Indicators, reference values, scoring rules, and interpretation criteria would need to be adapted to local environmental, socioeconomic, institutional, and production conditions.

This distinction is particularly important because sustainability is inherently context-dependent. The international value of SUSTIN-OLIVA therefore lies primarily in its potential to provide a common digital structure for collecting, processing, and interpreting multidimensional sustainability information while allowing the content of the assessment to reflect local priorities. The framework should consequently be considered a potentially transferable digital architecture rather than a universal set of sustainability indicators. Application in other Mediterranean or developing-country contexts would require independent validation, stakeholder engagement, and contextual adaptation before broader implementation.

In the Tunisian context, where olive cultivation represents both an important economic activity and a component of cultural and territorial heritage, the findings have several policy implications. Beyond productivity-oriented interventions, public policies could place greater emphasis on ecological stewardship, territorial governance, collective action, and farm-level resilience. Strengthening farmer organizations, participatory monitoring mechanisms, knowledge exchange, and decentralized governance could contribute to reinforcing the socio-territorial dimension of sustainability. Similarly, the identification of indicators with comparatively weaker contributions provides an evidence-informed basis for targeting technical assistance, capacity building, infrastructure, or institutional support, while stronger indicators can be considered existing assets to be consolidated. Importantly, SUSTIN-OLIVA does not prescribe specific policy interventions; rather, it provides a structured information base that can help policymakers and stakeholders identify areas requiring attention, compare sustainability patterns, and formulate more context-sensitive strategies along agroecological transition pathways.

Several limitations should be considered when interpreting the results. First, the empirical application of SUSTIN-OLIVA was based on a relatively small sample of 61 olive farms selected through a purposive, non-probabilistic sampling strategy in two agroecological areas of Tunisia. Although this approach was appropriate for capturing contrasting farming contexts and practices associated with agroecological transition, the sample is not statistically representative of the Tunisian olive sector and therefore limits the generalizability of the findings. Likewise, the inclusion of only two agroecological zones does not capture the full diversity of Tunisian olive-farming systems, particularly the substantial differences in climatic conditions, production intensity, water availability, and socioeconomic contexts observed across the country.

Second, PCA was employed as an exploratory technique to investigate the internal structure and relationships among sustainability indicators rather than as a definitive validation procedure. Given the relatively limited sample size in relation to the number of indicators considered, the stability of the component structure and the identification of retained indicators may be sensitive to the characteristics of the sampled farms. The PCA results should therefore be understood as empirical evidence supporting the internal coherence and exploratory usefulness of the indicator framework within the study sample, rather than as evidence of universal validity. SUSTIN-OLIVA has not yet undergone external validation using an independent sample or in agroecological contexts beyond those

considered here. Future research should therefore test the robustness and transferability of the framework using larger and more diverse samples covering additional Tunisian agroecological regions and production systems. Such validation could subsequently be extended to other Mediterranean olive-farming systems to determine which indicators and relationships remain relatively stable across contexts and which require contextual adaptation. Longitudinal studies would also be valuable for assessing whether repeated use of the digital framework can support monitoring of changes in farm practices and sustainability performance over time. These steps would strengthen the methodological robustness and external validity of SUSTIN-OLIVA and clarify its potential as a transferable decision-support framework for sustainability assessment in Mediterranean agriculture.

5. Conclusions

This study presents the development and application of the SUSTIN-OLIVA digital framework as an integrated, indicator-based system for exploring sustainability in Tunisian olive farming systems undergoing agroecological transition. The framework operationalizes sustainability through a structured set of environmental, economic, and socio-territorial indicators embedded within a digital decision-support environment designed to enhance data integration, comparability, and usability at farm level.

PCA was used as an exploratory approach to examine the internal structure of the sustainability dimensions and the contribution of individual indicators to the observed factorial structure. The results highlight differentiated contributions across the three sustainability dimensions, with economic indicators showing a prominent role within the observed sustainability structure, while environmental and socio-territorial indicators contribute in complementary and context-dependent ways. These findings should be interpreted as associations within the study sample rather than as evidence of causal relationships or as a universal ranking of sustainability performance.

The socio-territorial dimension, although more heterogeneous in its expression, remains essential for capturing the multifunctional role of olive agroecosystems, particularly in terms of territorial identity, local knowledge, collective practices, and social cohesion. Environmental sustainability is mainly structured around resource efficiency, natural-resource management, and circularity-oriented practices, whereas economic indicators show comparatively stronger contributions within the observed sustainability structure, highlighting the relevance of financial viability and economic resilience in the context of agroecological transition.

Importantly, the analysis also demonstrates the value of complementing indicator-level analysis with a farm-level perspective. The differentiated farm profiles identified through PCA reflect distinct combinations of environmental, economic, and socio-territorial characteristics rather than a simple hierarchy of more or less sustainable farms. This farm-level heterogeneity highlights that farmers may follow different combinations of practices, strategies, resources, and territorial engagements during agroecological transition. Consequently, sustainability-oriented interventions should not necessarily follow a uniform approach, but may benefit from being adapted to the characteristics, constraints, and capacities of different groups of farms.

The reference farm further illustrates the usefulness of a farm-level perspective as a benchmark or illustrative case rather than as a statistically representative standard. Its distinct position in the factorial space highlights a particular combination of sustainability attributes that may provide transferable lessons, while recognizing that the relevance and transferability of specific practices depend on farm structure, production systems, resource availability, and local conditions.

Beyond its empirical findings, the main contribution of this study lies in the development and application of a digital environment that organizes multidimensional sustainability indicators and facilitates their analysis and interpretation. By integrating environmental, economic, and socio-territorial information into a unified digital architecture, SUSTIN-OLIVA contributes to the operationalization of sustainability assessment and supports data-driven and decision-oriented approaches. This aligns with recent developments in digital agriculture and sustainability analytics, where integrated platforms are increasingly recognized as tools for supporting evidence-based management and governance. From a practical perspective, the application provides a structured basis for identifying sustainability areas requiring attention, exploring differentiated farm profiles, and supporting farm-level monitoring and decision-making. At a broader level, aggregated sustainability information could contribute to the targeting of agricultural interventions and the design of evidence-based policies for agroecological transition.

The findings therefore support a complementary use of SUSTIN-OLIVA at different analytical scales. At the indicator level, the framework helps identify sustainability attributes that contribute relatively strongly or weakly to the observed structure and may therefore inform areas requiring consolidation or further attention. At the farm level, it helps reveal how these attributes are combined within individual holdings and supports the identification of differentiated farm profiles. Together, these two levels provide a basis for moving from sustainability measurement towards more targeted strategies, in which territorial policies can address broader structural or institutional priorities while farm-level interventions can be adapted to the specific characteristics and needs of farmers.

Future research should focus on the external validation of SUSTIN-OLIVA using larger and independent samples across broader agroecological and socio-economic contexts, with particular attention to the reliability, accuracy, usability, and consistency of its outputs. Further studies should examine the expression of selected socio-territorial and environmental indicators and assess the framework across different agroecological settings. Longitudinal studies would be valuable to better understand sustainability dynamics and agroecological transition pathways over time. A complementary research line should further investigate farm typologies and the relationships between sustainability profiles and farmers' behaviours and decision-making processes, including agricultural practices, marketing strategies, training, associative involvement, and environmental engagement. The role of agroecological context in differentiating farm sustainability profiles should also be examined, together with multicriteria approaches for positioning and comparing farms, including their relative position with respect to the reference farm. Further development of data interoperability and digital integration could enhance the use of sustainability information for monitoring, comparison, and strategic planning. Future developments could also explore the integration of remote sensing, IoT-based observations, and other digital data sources to complement farm-level indicators, as well as the adaptation of the framework to other Mediterranean and developing-country farming systems.

Overall, SUSTIN-OLIVA provides a structured digital approach for exploring multidimensional sustainability in olive farming systems and for linking indicator-level information with differentiated farm-level sustainability profiles. Its application in the Tunisian case study illustrates the potential of combining digital sustainability assessment with exploratory multivariate analysis to make sustainability patterns more visible at both indicator and farm levels. This provides a basis for moving from measurement towards context-sensitive strategies, while recognizing the diversity of farmers and farming systems and the need for further validation before broader application. In this respect, SUSTIN-OLIVA represents not a universal ranking or fixed set of sustainability solutions, but a

potentially adaptable digital decision-support framework for informing agroecological transition and strategic interventions in Mediterranean olive production systems.

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Institutional Review Board Statement: This study involved a non-interventional survey with olive farmers. No personal or sensitive information was collected, and all data were handled confidentially. Participation was voluntary, and the collected information was used exclusively for research purposes. According to institutional guidelines, ethical approval was not required for this type of anonymous agricultural survey.

Informed Consent Statement: Not applicable, as verbal informed consent was obtained from all participants prior to the interviews.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

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Abbreviations

CSR	Corporate Social Responsibility
SDK	Software Development Kit
GDA	Groupement de développement Agricole
IDEA	Indicateurs de Durabilité des Exploitations Agricoles (Farm Sustainability Indicators)
MESMIS	Marco para la Evaluación de Sistemas de Manejo de Recursos Naturales incorporando Indicadores de Sustentabilidad
PCA	Principal Component Analysis
PDO	Protected Designation of Origin
PGI	Protected Geographical Indication
RISE	Response-Inducing Sustainability Evaluation
SAFA	Sustainability Assessment of Food and Agriculture systems
SMSA	Société Mutuelle de Service Agricole
SUSTIN-OLIVA	SUSTainability framework IN agroecological OLIVE farming systems
TAPE	Tool for Agroecology Performance Evaluation

Appendix A

Table A1. Socio-Territorial Dimension of Sustainability: Indicators and Scoring Framework.

Sustainability Dimension	Evaluation Criteria	Indicators (Expected Situation Compared to the Initial Situation)	Scoring Calculation
ST 1	Local Dynamic and territorial anchorage	ST1.1. Good governance: – SMSA. – GDA. – Consortium. – Fair Trade.	0 if no measure is applied for the indicator 2 if at least one measure is applied
		ST1.2. Promotion of local know-how: – Traditional processing of agricultural products. – Promotion of Typical Gastronomy. – Typical agricultural products. – Typical artisanal products	0 if no measure is applied for the indicator 1 if at least one measure is applied
		ST1.3. Involvement in community life and local engagement: – Civil society participation. – Collaboration with local developers. – Technical support. – Involvement in scientific research. – Attendance at seminars and workshops. – Participation in agricultural products competitions.	0 if no measure is applied for the indicator 1 if one measure is applied 2 if more than two measures are applied
		ST1.4. Valorization through quality labels indicating origin and local know-how: – PDO. – PGI.	0 if no measure is applied for the indicator 2 if at least one measure is applied
		ST1.5. Valorization of the multifunctionality of agriculture: Agrotourism projects or any initiative that highlights agricultural functions and services beyond production.	0 if no measure is applied for the indicator 1 if at least one measure is applied
			The maximum cumulative score for this criterion ST 1 is: 8 points
ST 2	Valorization through short supply chains	This sustainability criterion aims to assess the strengthening of the link between producer and consumer, especially considering the large number of intermediaries in the olive oil sector. Under this criterion, any initiative aimed at strengthening the producer consumer relationship is considered: – Direct sale to the final consumer (either directly or through specialized markets). – Control over the entire value chain: production–processing–marketing. – Existence of a producer–processor contract. – The farmer owns a commercial brand and markets all or part of their product in packaged form. – Vertical integration through into commercialize the final product through a society. – Improved product traceability, ensuring better quality and building trust between producer and consumer.	A scoring system may be applied for each measure: 0 if the farmer does not adopt any measure aimed at short supply chain valorization (e.g., selling olives to an intermediary) 2 if the farmer adopts one measure aimed at short supply chain valorization 5 if the farmer adopts two or more measures aimed at short supply chain valorization

Table A1. Cont.

Sustainability Dimension	Evaluation Criteria	Indicators (Expected Situation Compared to the Initial Situation)	Scoring Calculation
			Maximum cumulative score for this criterion ST2: 5 points
ST 3	Corporate Social Responsibility	This criterion evaluates the company's commitment to society through responsible actions, particularly regarding human capital and local development. The indicators defining this criterion are as follows: ST3.1. Workplace hygiene and safety: this indicator includes all measures related to workplace hygiene and safety, as well as worker protection and security during their tasks: – Wearing masks during phytosanitary treatments. – Decent transportation for workers. – Equipment maintenance. – Insurance for permanent workers and equipment. ST3.2. Involvement of young graduates. ST3.3. Farm viability through generational renewal. ST3.4. Engagement through local development projects Through fair trade, companies are responsible for implementing development projects in the concerned areas (as required by the specifications).	Scoring system for the indicators: 0 if no measure is applied for the indicator 3 if at least one measure is applied 5 if the farmer adopts two or more measures.
			Maximum cumulative score for this criterion ST3: 5 points
ST4	Farmers' quality of life	This indicator assesses the quality of life of farmers, in other words, whether agriculture as a source of income can provide the essential elements for living a healthy and comfortable life. – Through agriculture, the farmer can feed themselves and their family three meals per day, including fruits, vegetables, and meat. – Agriculture allows the farmer to provide appropriate clothing for themselves and their family, including shoes, clean clothes for school or work, and warm clothing. – Ability to cover children's education costs. – Access to medical care, including doctor visits for themselves and their family, and the ability to purchase prescriptions or medication. – A sufficient amount of clean drinking water at home. – Access to safe means of transportation. – Safe housing that protects against weather conditions. – Energy expenses that ensure adequate lighting and heating.	Scoring system for the indicators 0 If agriculture does not allow for the achievement of any of the above criteria. 1 If agriculture allows for the achievement of at least one of the above criteria. 4 If agriculture allows for the achievement of several of the above criteria.
			Maximum cumulative score for this criterion ST4: 4 points

Table A1. Cont.

Sustainability Dimension	Evaluation Criteria	Indicators (Expected Situation Compared to the Initial Situation)	Scoring Calculation
ST 5	Job creation and retention/ Inclusion of women, youth, and decent work	ST5.1. Share of women among workers - There are women working on the farm, and their percentage exceeds 40%	0 No women working on the farm 1 If % of women exceeds 40%
		ST5.2. Share of youth (< 40 years old) among workers - There are young people working on the farm, and their percentage exceeds 40%	0 No young people (<40 years old) work on the farm 1 If yes
		ST5.3. Formalization and decency of employment - Formal employment (employment contract, payslip) - Remuneration higher than the minimum wage (SMAG) - CNSS insurance and/or complementary insurance for employees	0 If no measure is adapted. 1 If one measure is adapted. 2 If at least two measures are adopted.
		ST5.4. The project includes capacity building, training related to ecological transition, and/or the recruitment of qualified personnel - Training of the project leader and/or the project leader is qualified -Training of staff and. - Recruitment of qualified personnel.	0 If no measures 2 If one measure 3 If at least two measures
			Maximum cumulative score for this criterion ST5: 7 points
ST6	Territorial embeddedness	The investment project is linked to one or more of the following elements contributing to local social and territorial dynamism: - Local support/entrepreneurship mechanisms (business centers, coaching, spaces, etc.) or development/research projects or programs - Membership in a professional organization/association active in ecological transition, - Producer services, conservation of local breeds and varieties, etc. - Regular advisory support (technical or techno-economic) by a local provider: veterinarian, agricultural technician, etc. - Territorial planning and concerted resource management	Scoring system: 0 None of the measures below 1: one or 2 of the measures below 3: More than 2 of the measures below Bonus: 1 fair-trade certification
			Maximum cumulative score for this criterion ST6: 4 points
Maximum cumulative score for the socio-territorial dimension = 33 points			

Table A2. Environmental Dimension of Sustainability: Indicators and Scoring Framework.

Sustainability Dimension	Evaluation Criteria	Indicators (Expected Situation Compared to the Initial One)	Scoring Calculation
Env 1	Adoption of agro-ecological principles	Env1.1. Selection of local varieties adapted to climatic conditions Potential varieties: Chemlali in central Tunisia, Chetoui in the north.	0: No one 2: If one is adopted 4: If at least Two are adopted
		Env1.2. Crop diversification and livestock integration – Crop association or livestock integration only – Livestock	0: No diversification 2: If one is adopted 4: If two are adopted
		Env1.3. Soil and water conservation Agroecological measures: – Rainwater harvesting (CES works, Meskat) – Proper tillage (perpendicular to slope) – Conservation agriculture (no-till, direct seeding) – Organic fertilization (manure, compost, biochar) – Cover crops – Natural hedgerows	0: No measure adopted 2: One agroecological measure adopted 4: More than two measures adopted
		Maximum cumulative score for this criterion Env 1: 12 points	
Env 2	Adoption of circular economy principles	Env2.1. Valorization of by-products Examples: – Use of pruning wood for charcoal or crafts – Use of leaves/twigs for animal feed or compost – Reuse of olive mill waste (olive mill waste water, olive cake) for soil fertilization—Separation and use of pulp/seeds – Product quality improvement and traceability	0: No measure adopted 2: One measure adopted 5: More than two measures adopted
		Env2.2. Recycling and sustainable waste management (non-agricultural waste) Examples: – plastic bottles – irrigation pipes – empty containers of agro-inputs	0: No recycling measures 1: Some recycling measures adopted
		Env2.3. Use of renewable energy – solar panels – energy-saving practices	0: No energy-saving measure 5: Use of renewable energy
		Maximum cumulative score for this criterion Env 2: 11 points	

Table A2. Cont.

Sustainability Dimension	Evaluation Criteria	Indicators (Expected Situation Compared to the Initial One)	Scoring Calculation
Env3	Efficiency in water use in the production process (Water productivity)	The production of olive oil requires large amounts of water along the value chain, from farming to transformation. Water use efficiency involves two main components: Env3.1. Efficiency of water supply management Potential measures: – Modernization of irrigation networks – Regular maintenance of irrigation infrastructure – Use of innovative systems to meet plant water needs (e.g., mycorrhizae) – Use of regulated deficit irrigation and partial root-zone drying (PRD)	0: No measure adopted 3: One measure adopted 5: More than one measure adopted
		Env3.2. Water demand management Potential measures: – Use of decision-support tools for irrigation management (to meet real crop needs and avoid waste) – Use of integrated technical packages to optimize both production and water consumption	0: No measure adopted 3: One measure adopted 5: More than one measure adopted
		Maximum cumulative score for this criterion Env 3: 10 points	
		Maximum total score for environmental sustainability dimension: 33 points	

Table A3. Economic Dimension of Sustainability: Indicators and Scoring Framework.

Sustainability Dimension	Evaluation Criteria	Indicators (Expected Situation Compared to Initial Situation)	Scoring Calculation
Eco 1	Income levels	Proposed income ranges:	1: 330–1000 TND 3: 1001–3000 TND 5: 3001–6000 TND 7: 6001–10,000 TND 10: > 10,000 TND
		Over the last 5 years, have revenues exceeded expenses? At what level?	5: All or most of the time 3: Some of the time 1: Rarely
		Maximum total points for the criterion Eco 1: 15 points	

Table A3. *Cont.*

Sustainability Dimension	Evaluation Criteria	Indicators (Expected Situation Compared to Initial Situation)	Scoring Calculation
Eco 2	Savings	Yes/No	0 If No 3 If yes
		Maximum total points for the criterion Eco 2: 3 points	
Eco 3	Income stabilization	Diversification of sources of income (pluri-activity)	0: Agriculture only 4: Other activities in addition to agriculture
		Maximum total points for the criterion Eco 3: 4 points	
Eco 4	Diversification (value chain and added value)	Diversification of agricultural products, supply sources, and product distribution channels:	0: No diversification 1: Limited diversification (+1 product/source/channel) 2: Moderate diversification (+2 to 3 products/sources/channels) 4: Significant diversification (more than 3 products/sources/channels)
		Maximum total points for the criterion Eco 4: 4 points	
Eco 5	Securing supply and insurance	ECO 5.1. Securing supply sources and markets: – Agreements – Contracts – Input autonomy	ECO 5.1. 0: No contracts and dependence on imported inputs 2: Slight gain in autonomy and/or contract covering less than 30% of production 4: Significant gain in autonomy and/or contract covering more than 30% of production
		ECO 5.2. Insurance: – risks related to climate hazards – Fires – Hail – Floods – drought	ECO 5.2. 0: No insurance 2: Insurance covering a limited part of production (<30%) 4: Insurance covering a significant part of production (>30%) Maximum total points for the criterion Eco 5: 8 points
Maximum total score for the economic dimension: 34 points			

Appendix B. Illustrative Examples of SUSTIN-OLIVA Questionnaire Interfaces

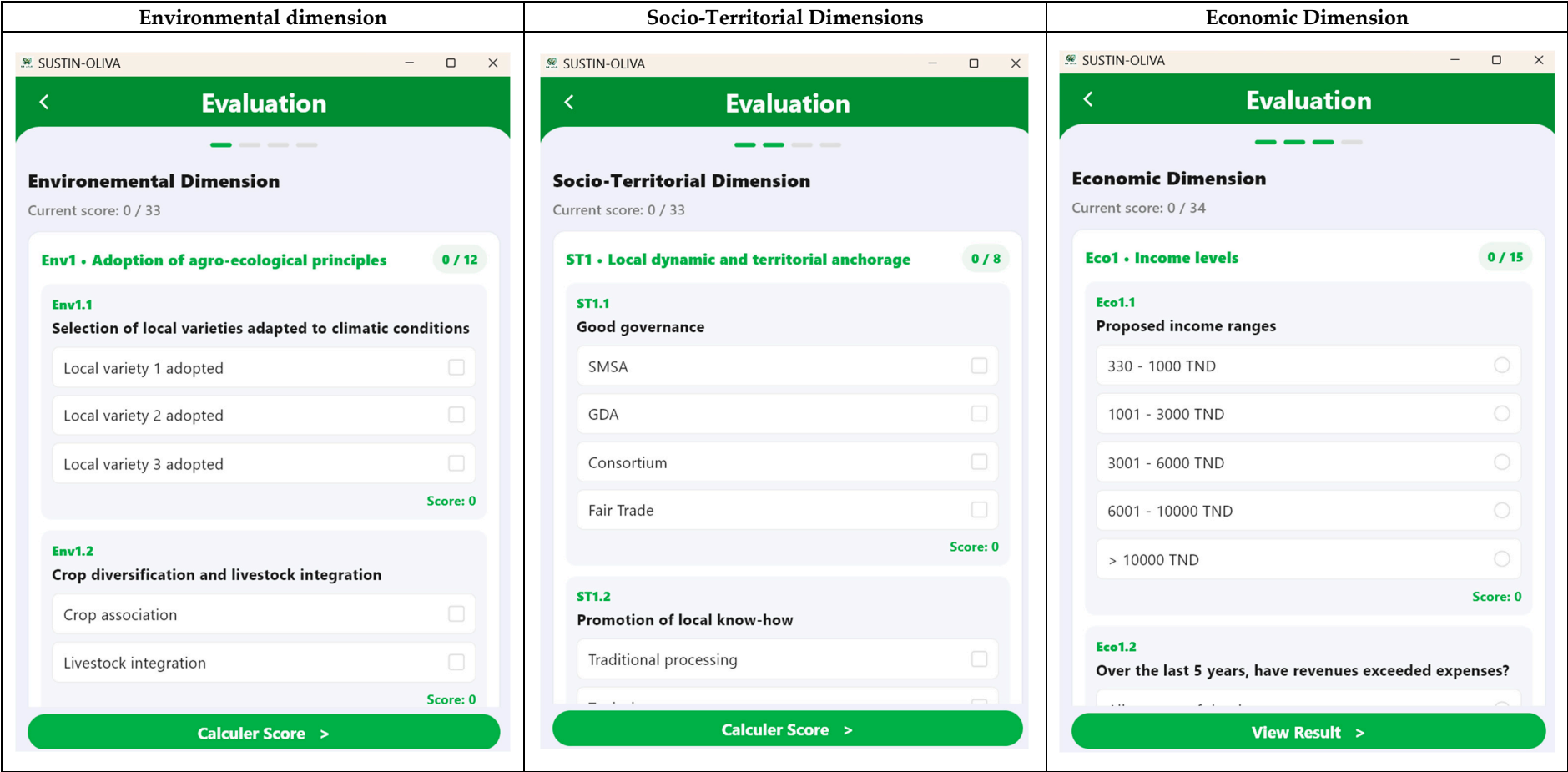


Figure A1. Illustrative Examples of SUSTIN-OLIVA Questionnaire Interfaces.

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