SMALLDERS PROJECT

SMART **M**ODELS FOR **A**GRIFOOD **L**OCAL VA**L**UE CHAIN BASED ON **D**IGITAL TECHNOLOGIES FOR **E**NABLING COVID-19 **R**ESILIENCE AND **S**USTAINABILITY

D6.4

Definition of multi-capitals sustainability indicators

The PRIMA programme is an Art.185 initiative supported and funded under Horizon 2020, the European Union's Framework Programme for Research and Innovation.

Project Information

Acronym: SMALLDERS

Title: **S**mart **M**odels for **A**grifood **L**ocal Va**L**ue Chain Based on **D**igital Technologies for **E**nabling Covid-19 **R**esilience and **S**ustainability

Coordinator: The University of Calabria (Italy)

Programme: PRIMA. Thematic area Agro-food value chain. Topic 2.3.1

Start: 2022-05-01

Duration: 36 months + 6 months of extension

Web: https://mel.cgiar.org/projects/smallders

Consortium:

University of Calabria, Italy (UNICAL)

University of Parma, Italy (UNIPR)

University of Extremadura, Spain (UEX)

IMT Mines Ales, France (LSR)

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DELIVERABLE

Number: D6.4

Title: Definition of multi-capitals sustainability indicators

Lead participant: Faculty of Science of Tunis, Tunisia (LAPER)

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Work package: WP6

Dissemination level: Public (PU)

Type: Report (R)

Due date: 2025-04-30

Submission date: 2025-04-30

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Document revision

Version	Date	Editor	Overview
First release	2025-03-02	LAPER	Release of the first version
Second release	2025-04-04	LAPER	Release of the second version
Review	2025-04-15	UNICAL	Internal Review
Final release	2025-04-22	LAPER	Final release of the document

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AFSC	Agri-Food Supply chain
FQFD	Fuzzy Quality Function Deployment
FFD	Fossil Fuel Depletion
QFD	Quality Function Deployment
HOQ	House of Quality
WSF	Water Scarcity Footprint
WF	Water Footprint
WA	Water Availability
WS	Water Stress
WUE	Water Use Efficiency
ISI	Innovative Sustainability Index
TFP	Total Factor Productivity
EP	Eutrophication Potential
AP	Potential Acidification
FFD	Fossil Fuel Depletion
GHG	GreenHouse Gas
GWP	Global Warming Potential
CO_2	Carbon dioxide
NO_X	Nitrogen oxides
SDG	Sustainable Development Goal

EXECUTIVE SUMMARY

This deliverable refers to task T6.3 of WP6 of the SMALLDERS project, titled " Definition of Innovative sustainable indicators". Its purpose is to define relevant multi-capitals sustainability indicators essential for the dynamic dashboard layer enabling effective assessment of the Agri-Food Supply Chain (AFSC) performance. In previous deliverables, D6.1, D6.2, and D6.3, the study of the sustainability context for smallholders, the identification of multi-capital sustainability mathematical models, and the conceptualization of AFSC multi-capital sustainability scenarios were conducted, respectively. Based on these and D2.4's outputs, deliverable D6.4 proposes a methodology for selecting the final lists of multi-capital sustainability indicators for AFSC actors to design the SMALLDERS dashboard layer. Proposing a short set of essential metrics benefits all AFSC actors, notably smallholders. A reduced number of indicators makes data interpretation easier, enabling users to quickly and efficiently understand critical information while preventing system overload on the platform and enhancing decision-making processes.

1 Introduction

The D6.4 aims to define a final set of critical multi-capitals sustainability indicators for each AFSC actor, including smallholders, transportation companies, stakeholders, policy-makers, and citizens. These final lists of indications per actor define a customized dashboard for each, directly improving their decision-making abilities. Indeed, numerous remedial measures can be implemented using the simulation supplied by the decision-making layer under various scenarios. These simulations and their outcomes will feed back into the system, enabling the dashboard to be continuously updated with more accurate, scenario-based data to support informed and adaptive decision-making.

A preliminary list of indicators for each AFSC actor has already been defined via the previous deliverables (D2.4 and D6.3). Therefore, D6.4 will provide a final list of indicators for each AFSC actor. Given that the smallholders are the most vulnerable and important actors in the AFSC, an innovative sustainability index is proposed to help them better analyze the sustainability of their activities in monetary terms.

This D6.4 is divided into two parts. The first one will present the methodology for selecting the final list of smallholders' indicators. The Fuzzy Quality Function Deployment (FQFD) approach is used in this methodology, and an innovative sustainability index is defined using the Total Factor Productivity approach. The second part of this deliverable will define the final list of indicators for other AFSC actors, including transport companies, critical stakeholders, policy-makers, and citizens. To achieve this, additional tools from the literature will be explored.

2 Proposed approach for defining final list of sustainability indicators for *smallholders*

The proposed methodology for defining the final list of sustainability indicators for smallholders is presented in Figure 1. As a starting point, this approach is based on the analysis of smallholders' requirements and an initial list of multi-capital indicators, as specified in deliverables D2.4 and D6.3, respectively. As shown in Figure 1, three main steps were identified. First, experts in AFSC were surveyed, and initial data was collected. Then, the second step involved applying the FQFD process, a powerful tool for ranking and defining smallholders' most relevant multi-capital indicators based on their needs (Gunduz et al., 2021). This process began with sub-step 1, where the importance of each capital was determined through expert evaluations. In fact, experts were asked to rate the relevance of capitals using a predefined linguistic scale. In sub-step 2, relationships between the capitals and the initial list of indicators were established, highlighting how each indicator aligned with specific capital needs. Sub-step 3 involved developing a correlation matrix of the indicators to examine potential interactions or conflicts between them. In sub-step 4, the indicators were ranked using crisp scores providing a clear prioritization of the indicators. Finally, in sub-step 5, the results were discussed, leading to the selection and validation of the most relevant indicators for smallholders. The final step is dedicated to proposing an innovative sustainability index based on Total Factor Productivity approach.

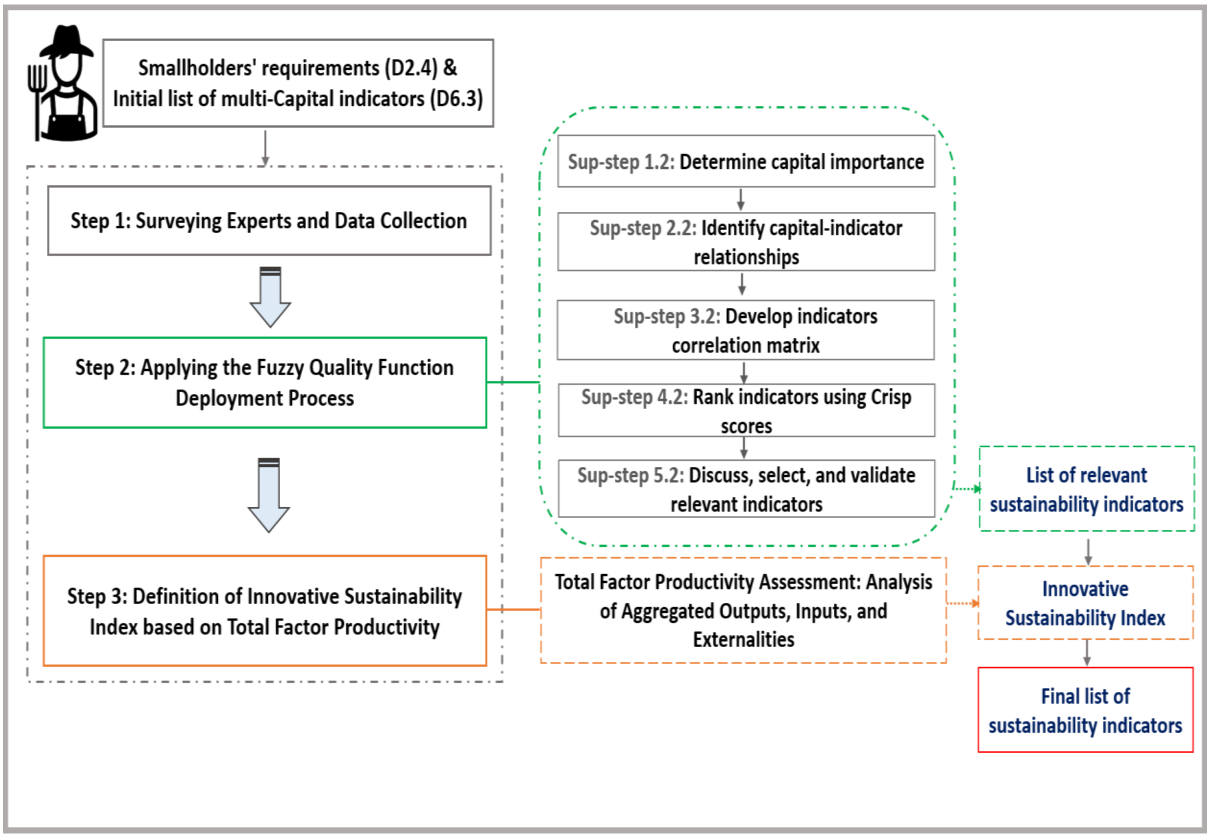

Figure 1 Proposed methodology for defining multi-capitals indicators for smallholders.

2.1 Surveying Experts and Data Collection

The initial stage of the FQFD process involves surveying experts to gather essential data that will support decision-making tailored to the AFSC context. The questionnaire was limited to feedback from Tunisian experts because the a priori list of indicators for each actor in D6.3 was based on an in-depth study of the state of the art mostly focusing on case studies from the European Union context. So, interviews with Tunisian experts were conducted to analyze the relationships between inter-indicators, indicators/capitals, and inter-capitals. Its goal is to assess the degree of links between these elements. The questionnaire, developed and distributed through Google Forms, enabled experts to answer a series of structured questions (e.g., assessing the importance of each capital type or evaluating the relationships between sustainability indicators and capitals).

Three Tunisian experts with diverse profiles participated in the study: the first one is an agricultural economics engineer specializing in sustainable resilient agroecosystems; the second is an expert in sustainable development and climate change; and the third is an agronomy consultant. Online meetings were held with these experts to explain the SMALLDERS project, the dashboard layer's aim and define the involved sustainability capitals and indicators, and the questionnaire's purpose. This last one is divided into two main sections. The first section, "Capital Importance and Indicator-Capital Relationship," assesses the significance of each capital type and the relationships between indicators and capitals. The second section, "Indicator-Indicator Relationship," explores potential interactions among various sustainability indicators. Each question represents a specific relationship and is presented in table format allowing experts to check appropriate boxes based on their assessments.

2.2 Fuzzy Quality Function Deployment

The FQFD approach is used to define and prioritize sustainability indicators for smallholders. The Quality Function Deployment (QFD) is a structured method used to transform smallholders' requirements and expectations into specific sustainability indicators (Puglieri et al., 2020). The decision to apply FQFD stems from its ability to manage uncertainty and core benefits of QFD itself. QFD systematically translates smallholders' needs into clear sustainable indicators. It helps prioritize indicators based on their importance to smallholders, improving decision-making and relevance (Baidya et al. 2018). Combined with fuzzy logic, QFD becomes even more powerful by addressing the ambiguities in expert judgments and subjective evaluations. Qualitative attributes used in surveys are often expressed in linguistic terms, making it difficult for traditional quantitative methods to capture their subjective meanings. Fuzzy logic offers a robust solution for converting subjective judgments, such as the importance of capitals, relationships, and correlation matrices, into usable numerical values, allowing for a more accurate analysis of sustainability indicators (Singh and

Kumar, 2021). This combination provides a robust framework for determining a list of the most relevant smallholders' indicators. To implement the algorithms for the proposed FQFD method MATLAB software is used.

The QFD approach requires the development of House of Quality (HOQ) which is an approved tool wherein visually appealing graphical illustrations are used to convert smallholders' demands (WHATS) into technical qualities (HOWS) (Baidya et al. 2018). As shown in Figure 2, the HOQ is built into the following sections: the smallholder's requirements that are traduced to capitals (WHATS), the initial list of indicators (HOWS), capital Importance, relationship matrix (HOWS vs. WHATS), correlation matrix (HOW vs. HOW), and relative importance rating of indicators. Each step of the proposed methodology is explained in the following.

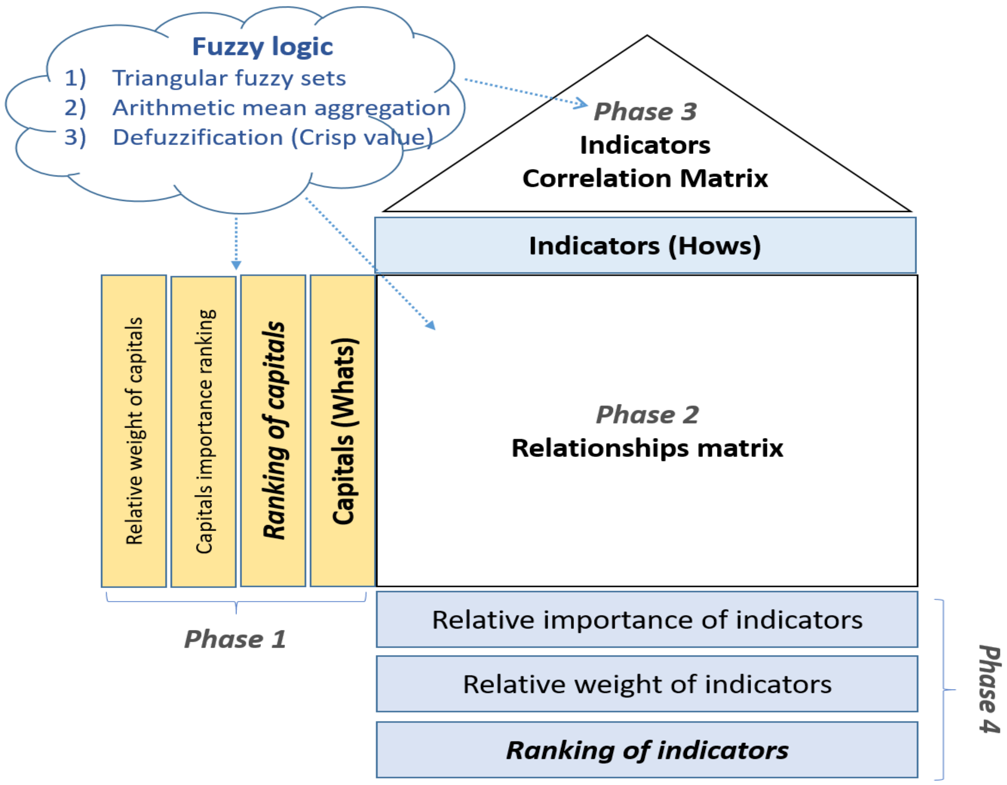

Figure 2 A view of a Fuzzy House of Quality and its processes.

The proposed FQFD began with phase 1, where the importance of each capital was determined through expert evaluations. Each expert established the capitals' importance weight using a range of linguistic terms to express varying levels of significance. Five weight levels for smallholder requirements are utilized in this study, with the judgment scale based on Saaty's rating (Saaty, 1990). The linguistic terms presented in Table 1 are inspired by (Javanbarg et al., 2012) and are quantified using triangular fuzzy numbers.

Table 1 Importance weights and corresponding fuzzy numbers for rating capitals

Linguistic terms	Scale of Importance	Fuzzy number
Not important (NI)	1	(0.5, 1, 2)
Slightly important (SLI)	3	(2, 3, 4)
Important (I)	5	(4, 5, 6)
Very important (VI)	7	(6, 7, 8)
Crucial (C)	9	(8, 9, 10)

To aggregate the fuzzy expert responses, the arithmetic mean method is applied as commonly used in recent studies on fuzzy logic and decision-making processes (Wu & Zeshui 2021).

This method consolidates individual expert assessments by calculating the average, facilitating a balanced representation of expert opinions within the analysis. From the aggregated fuzzy set, crisp values for the weights need to be obtained by defuzzification. For this purpose, the crisp value of a triangular fuzzy number a (l, m, u), is computed as follows (Vural & Tuna, 2016):

$$Crisp\ value = \frac{l+2*m+u}{4} \qquad (1)$$

Rank	Capital	Capital weight / importance
1	Natural	0.1543
2	Financial	0.142
3	Material	0.1296
3	Stakeholders	0.1296
3	Intellectual	0.1296
6	Human	0.1173
7	Internal Social	0.1049
8	External Social	0.0926

Figure 3 Ranked capitals.

As highlighted in Figure 3, natural and financial hold the highest weights among the attributes considered, indicating their significant importance for smallholders. On the other hand, smallholders place equal value on stakeholder, intellectual, and physical capital. The significance that smallholders place on the economic dimension is therefore crucial. To a lesser extent, human capital comes next. The remaining capital plays a moderate role in the overall priorities, suggesting they are necessary but of lesser importance than other needs.

In phase 2, a relationship matrix between capitals and indicators was designed. Each expert evaluated the impact of each indicator on each capital using the linguistic variables, adopted by (Gumus, 2009), given in Table 2. Triangular fuzzy numbers have been used for indicating the relationships matrix to overcome the vagueness of linguistic judgment. The arithmetic mean aggregation method was then applied to combine the fuzzy expert responses.

Table 2 Degree of relationships capital-indicator and corresponding fuzzy numbers

Linguistic terms	**Scale of Importance**	**Fuzzy number**
Similar importance (SI)	1	(1, 1, 1)
Moderate importance (MI)	3	(2, 3, 4)
Strong importance (SI)	5	(4, 5, 6)
Very strong importance (VSI)	7	(6, 7, 8)

The weights of the indicators, which are the main output of the HOQ, represent the final importance scores of the indicators. These weights are defined at the base of the quality matrix and are determined by:

$$Weight(KP_i) = \sum_{n=1}^{N} V(KP_{in}) \times imp(Capital_n)$$

where $V(KP_{in})$ is the relationships between indicator (KP_i) and capital ($Capital_n$), and $imp(Capital_n)$ represents the importance or priority of $Capital_n$N is the total number of capitals considered.

The final step, defuzzification, converts fuzzy weights into crisp scores for ranking the indicators. Based on crisp values, indicators are ranked in descending order with the highest score from the crisp values and the indicator with the highest relative weight being ranked number 1, as shown in Appendix 1.

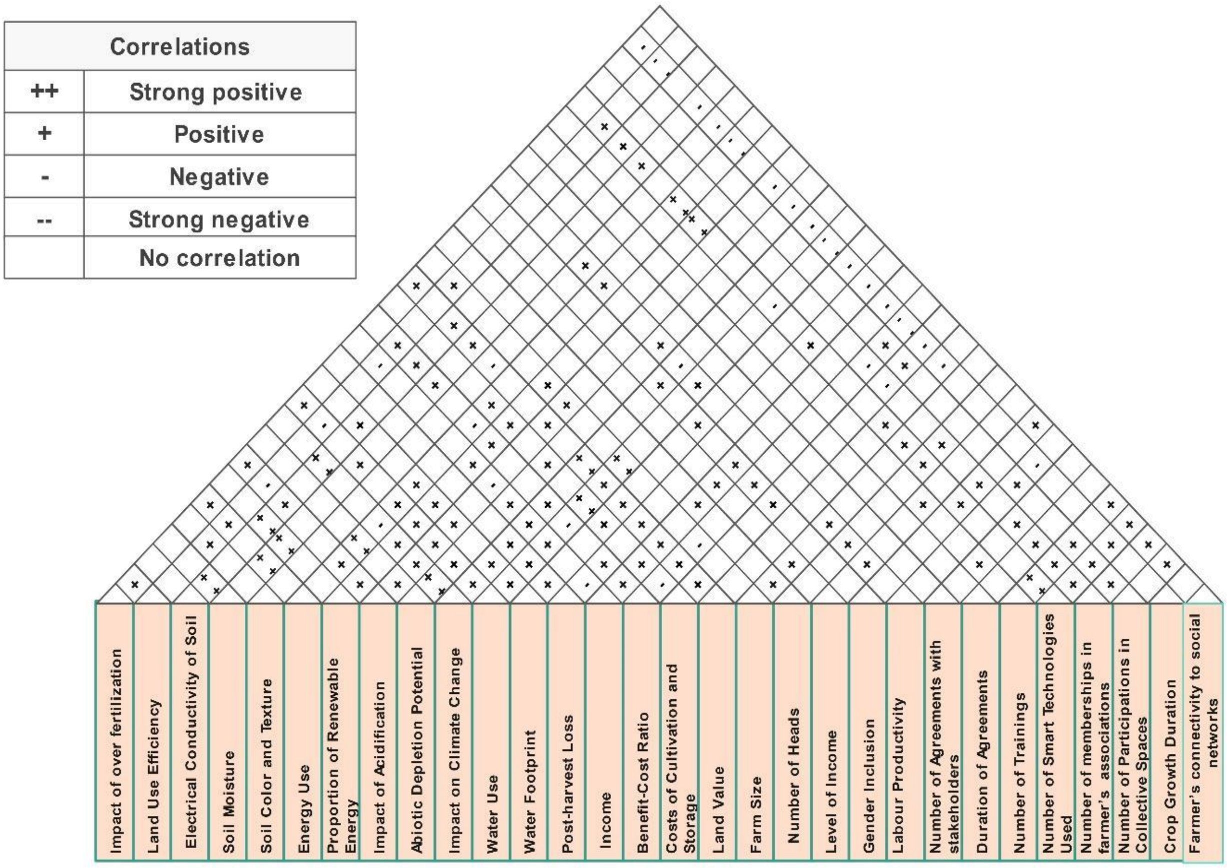

Figure 4 Indicators correlation matrix.

Phase 3 of the Fuzzy HOQ analyzes the correlations among indicators for smallholders. Different symbols are assigned to represent the strength of the indicators' relationships. This assessment, along with the graphic symbols and triangular fuzzy numbers, proposed by (Bottani, 2009), are presented in Table 3. The arithmetic mean aggregation and defuzzification are then applied. The results, presented as the roof of the HOQ, are illustrated in Figure 4.

Table 3 Degree of correlations, graphic symbol, and corresponding fuzzy numbers

Linguistic terms	Graphic symbol	Fuzzy number
Strong positive (SP)	++	(0.3, 0.5, 0.7)
Positive (P)	+	(0, 0.3, 0.5)
Negative (N)	-	(- 0.5, - 0.3, 0)
Strong negative (SN)	--	(- 0.7, - 0.5, - 0.3)
No correlation (NC)		(0, 0, 0)

The HOQ was designed using EdrawMax, a versatile diagramming software that enabled the design of complex matrices and the accurate representation of various relationships. This ensured a clear and structured layout for the FQFD analysis.

The contradictions between the indicators were determined using this correlation matrix. The pairs of indicators that showed a negative or strong negative correlation are deemed contradictory. These inter-indicator conflicts will be taken into account when determining the final selection of the final list of sustainable indicators for smallholders.

2.3 Discussion of Findings, Algorithm Selection and Final List

The analysis of the relationships between indicators and capitals for smallholders highlights key challenges and priorities. This investigation assesses the significance of relationships, relative weights, and ranking of indicators, as shown in Appendix 1. The multi-capital indicators outlined exhibit varying degrees of weight and relationship values crucial for smallholders.

The FQFD analysis highlights the importance of balancing relevant indicators with the specific needs of smallholders in each country included in the project, especially in Tunisia. Given that most smallholders in Tunisia have low educational levels, this concern was extensively discussed in our meetings with experts, who addressed it in their feedback. As a result, the experts offered various suggestions in order to give a simple and informative dashboard for smallholders. First and foremost, indicators must be defined with simple names that smallholders can understand. Second, the experts advised adding the indicator "crop growth time" to the initial set of indicators described in D6.3. Expert's perspective, this indicator directly affects how natural resources, particularly land, water, and energy, are used. Following the initial ranking provided by the FQFD methodology, a streamlined algorithmic selection approach is proposed to systematically select indicators based on specific retention and elimination criteria. The algorithm starts by creating a list of indicators and their rankings. It first identifies and preserves unique indicators for each capital. Next, it examines themes to find indicators with only one representative, keeping those among the lower-ranked ones in the selected list. The algorithm then generates a list of remaining indicators by removing those already selected and sorting them by their rankings in ascending order. Finally, it eliminates the lowest-ranked indicators until the selected list contains 19 indicators. The output is the list of relevant selected indicators that match the set criteria while retaining at least one indicator per capital and per theme, as shown in Figure 5.

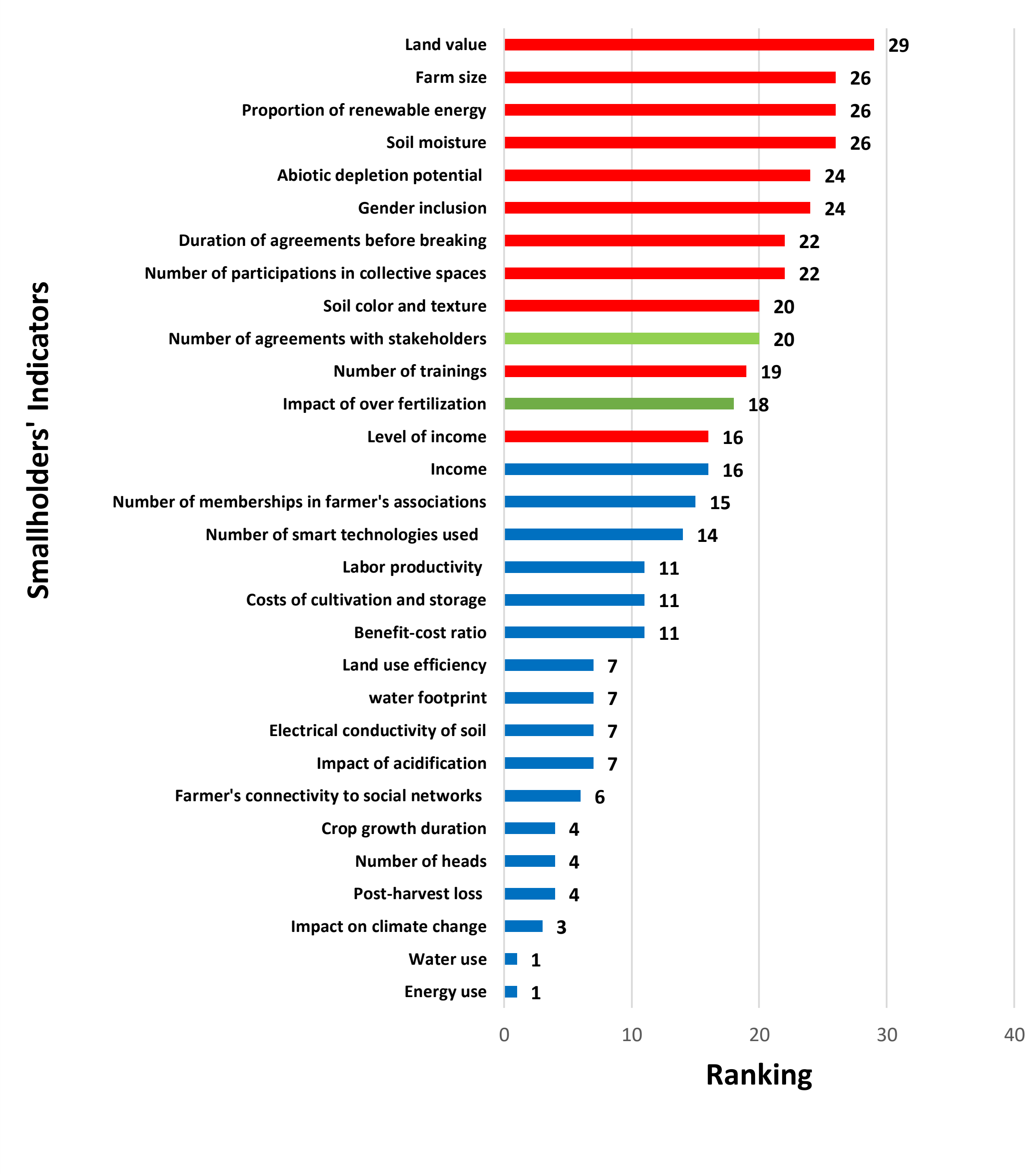

Figure 5 Final indicators ranking.

According to the experts' suggestions, certain indicators' names have been slightly changed to make it easier to grasp for smallholders. In effect, the indicator previously known as "eutrophication potential" has been renamed "impact of over fertilization." Similarly, "acidification potential" has been replaced by "impact of acidification," and "water used while farming" is now referred to as "water use." The "global warming potential" indicator will now be titled "impact on climate change". On the other hand, "social networks" has been changed to "farmer's connectivity to social networks. Finally, the "number of cattle" has been slightly modified to "number of heads" for more generality.

In addition, the Water Scarcity Footprint (WSF) indicator already defined in D6.3 was revised to Water Footprint (WF) due to its broader scope. Unlike the WSF, which focuses only on freshwater availability, the WF provides a comprehensive view by integrating blue, green, and gray water components (Elbeltagi et al., 2020). It has been widely used in case studies to assess smallholder sustainability, especially in regions with complex water use (Mulero et al., 2024).

Based on the ranking results, among the pivotal smallholders' indicators, energy use and water use hold paramount importance, securing the 1st position in terms of importance weight and ranking. The impact on climate change ranks 2nd, followed by post-harvest loss, number of heads, and crop growth duration, which share the 3rd position. Farmer connectivity to social networks holds the 4th position, followed by the impact of acidification, electrical conductivity of soil, WF, and land use efficiency. The benefit-cost ratio, costs of cultivation and storage, and labor productivity all share the same rank. Next is the number of smart technologies used, followed by the number of memberships in farmer associations. In the same rank are the income and the level of income, and finally, the impact of over-fertilization and the number of agreements with stakeholders.

The remaining 11 indicators (red bars) represent those that should not be considered in the final list. The impact of over-fertilization, shown as an orange bar, is ranked among the bottom 11; however, it is the only indicator representing the input theme, so it should be retained in the list. The green bar indicates an indicator that should be kept despite its moderately low ranking. The number of agreements with stakeholders should be preserved to maintain stakeholder capital after the indicator 'duration of agreements before breaking' has been eliminated. Consequently, the indicator level of income will also be ranked among the last to be eliminated.

Nineteen indicators, selected based on 8 sustainability capitals, serve as valuable tools for smallholders to comprehensively assess the sustainability of their activities. The list of relevant sustainability indicators is presented in Table 4.

Table 4 List of relevant sustainability indicators for smallholders

Capitals	Indicators	Unit
Natural	Impact of over-fertilization	Kg $PO4^{3-}$ eq ·year^{-1}
	Land use efficiency	kg ·ha^{-1} ·year^{-1}
	Electrical conductivity of soil	dS ·m^{-1}
	Energy use	Kwh ·year^{-1}
	Impact of acidification	kg SO_2 eq · year^{-1}
	Impact on climate change	kg CO_2 eq ·year^{-1}
	Water use	m3 per 10 min
	Water footprint	m^3 H_2O-eq ·year^{-1}
	Post-harvest loss	Kg ·year^{-1}
	Crop growth duration	Number of days
Financial	Income	TND (or Euros) ·year^{-1}
	Benefit-cost ratio	Dimensionless
	Costs of cultivation and storage	TND (or Euros) ·year^{-1}
Material	Number of heads	heads
Stakeholders	Number of agreements with stakeholders	Number ·year^{-1}
Intellectual	Number of smart technologies tools used	Number per 5 years
Human	Labour productivity	TND (or Euros) ·ha^{-1} ·year^{-1}
Internal Social	Number of memberships in farmer's associations (cooperative included)	Number per 5 years
External Social	Farmers connectivity to social networks	Number

2.4 Innovative Sustainability Index Based on Total Factor Productivity

According to the findings from the previous section, the economic dimension, particularly financial capital, is critical for smallholders. So, an indicator with a monetary value is easily more meaningful to smallholders. That's why it is proposed an Innovative Sustainability Index (ISI) for smallholders, based on Total Factor Productivity (TFP), a significant concept in agricultural economics over the last three decades (Kryszak et al., 2023). This ISI is a monetary assessment reflecting the sustainability of the smallholder's activities.

The methodologies proposed for estimating TFP in agriculture (Wang et al., 2019; Zhang et al., 2017; Xu et al., 2019) focus on assessing sustainability at the global supply chain level, while the proposed ISI stands out for its adaptation to the scale of actors within the Agri-Food Supply Chain (AFSC). The innovative index that we proposed is inspired by the work of Gaitán et al. (Gaitán et al., 2017). According to this last one, a modification of the formula is proposed to adapt it to the context studied while relying on the information collected for the calculation of the indicators already defined in the table 4. The index is based on the inclusion of new outputs, often referred to as "negative externalities" or "bad outputs" to explain the impact of smallholder practices on the environment.

In this context, the ISI is defined as the difference between the value of the aggregated final good outputs and the aggregated inputs and bad outputs, as proposed by (Gaitán et al., 2017):

$$ISI = Y - X_x - \alpha_k b_k$$

Where Y and X_x are the aggregate functions for outputs and inputs respectively. b_k represents the vectors of negative externality quantities which are aggregated through their corresponding shadow price vectors, denoted as α_k. A shadow price is the monetary value assigned to an abstract or intangible good or service that does not have an explicit market price but still impacts economic decision-making (Starrett, 2000).

The interpretation of this index is explained as follows: If the smallholder has a positive ISI, it indicates a sustainable activity, meaning he is managing the environmental impacts of their work without compromising economic viability. Conversely, a negative ISI indicates significant challenges, especially when environmental impacts outweigh inputs and good outputs.

Figure 6 summarizes the inputs, outputs, and negative externalities used for ISI calculation. The green, orange, and blue colors refer to environmental, economic, and social dimensions respectively. The inputs encompass the total costs belonging to the different capitals defined in our proposed framework (see D6.3): natural capital (costs of water use, energy consumption,..), financial capital, covering the costs of cultivation and storage; human capital, accounting for labor costs; intellectual capital which involves the costs of smart technology tools; material capital including the costs of equipment; internal social capital covering membership fees in farmers' associations; and external social capital by considering the costs of farmers' connectivity to social networks. The smallholder will need to enter the data needed to calculate some of the indicators listed in Table 4 for the dashboard layer design. As a result, smallholders won't need to provide any more data specifically for the ISI. Actually, the smallholder already provides the data on the total cost, which stands for

X_x, to calculate the benefit-cost ratio indicator. The outputs Y are then represented by the global income.

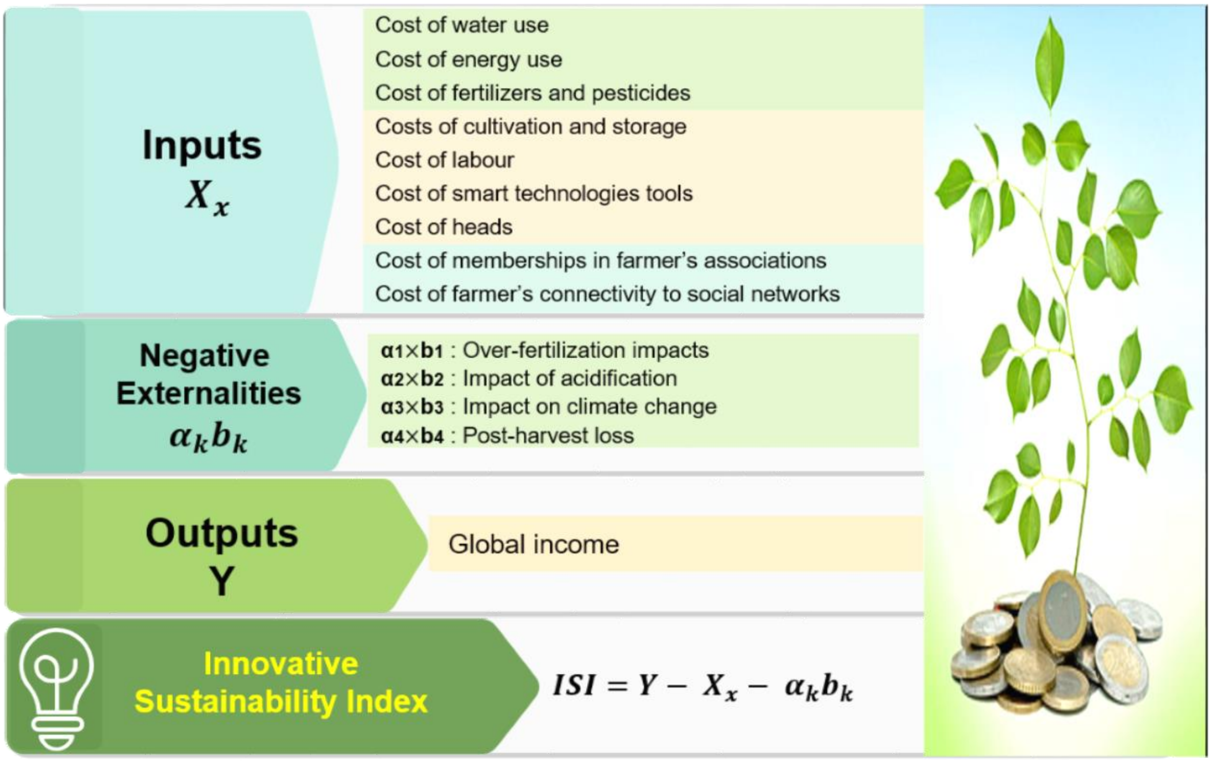

Figure 6 Presentation of inputs, outputs and negative externalities.

For smallholder, the production of crop generates four negative externalities: over fertilization impact (b_1), impact of acidification (b_2), impact on climate change (b_3) and post-harvest loss (b_4). Several studies and databases estimate the shadow prices of these negative externalities (Ståle, 2023; IEA, 2020; EC, 2022; CE Delft, 2018; UBA, 2019; EIB, 2023; NEEDS, 2009). To select an appropriate shadow price, the mean value of the estimates found in the aforementioned sources is computed. Table 5 summarizes the mean shadow prices that are calculated from the reports and sources, previously cited, adjusted to the Tunisian and European cases.

The mean shadow price of the over-fertilization impact is denoted as α_1, reflecting the economic cost associated with excessive fertilizer use, including nutrient runoff and its effects on water quality and ecosystems. The mean shadow price of the acidification impact is denoted as α_2, representing the economic cost linked to soil and water acidification caused by agricultural practices such as ammonia emissions and sulfur deposition. The mean shadow price of the impact of CO_2 emissions on climate change (α_3) includes those related to livestock, agricultural equipment, and soil/water disturbance, (IWG-SCC, 2021). Regarding post-harvest losses, the costs (α_4) are presented in this study according to a categorization by class or type of crop, as follows: cereals (e.g., wheat, maize), fruits (e.g., apples, bananas), and vegetables (e.g., tomatoes, carrots), as presented in several databases (CE Delft, 2018; NEEDS, 2009; EC, 2005).

Table 5 Mean shadow prices of one unit of negative externalities

Negative Externality	Mean shadow price	Sources
$\boldsymbol{\alpha_1}$	5 TND/kg PO_4^{3-} eq	(IEA, 2020) (CE Delft, 2018)
	15 €/kg PO_4^{3-} eq	(EC, *2022)* (CE Delft, 2018)
$\boldsymbol{\alpha_2}$	1.25 TND/kg SO_2-eq	(IEA, 2020)
	4 €/kg SO_2-eq	(CE Delft, 2018)
$\boldsymbol{\alpha_3}$	0.66 TND/Kg CO_2-eq	(IEA, 2020)
	0.175 €/Kg CO_2-eq	(UBA, 2019) (EIB, 2023)
$\boldsymbol{\alpha_4}$		
Cereals	0.280 TND/Kg	(NEEDS, 2009) (CE Delft, 2018)
	0.150 €/Kg	
Fruits	0.990 TND/Kg	
	0.400 €/Kg	
Vegetables	0.825 TND/Kg	
	0.350 €/Kg	

3 Frameworks from the Literature for Selecting Relevant Indicators for other AFSC Actors

A preliminary selection of indicators was defined for each actor based on the state of the art and the SMART method, according to specific, measurable, achievable, realistic, and time-bound criteria (see D6.3). In this deliverable, a second selection will refine the initial list by incorporating additional criteria, specifically model complexity for implementation, computational complexity for platform integration, and the necessity to reduce indicators for clarity and utility for AFSC actors. This is why; an in-depth state of the art is conducted, primarily based on case studies and surveys, along with consulting experts' opinions (experts presented in section 2.1) when necessary.

3.1 Relevant Indicators for Transport Companies

First, the literature was reviewed to inform the analysis and to explain why certain indicators were removed, as they were considered redundant or less relevant compared to other specific performance indicators. This approach emphasizes the significance of each indicator in our final selection. For the transport companies, the largest number of indicators is related to the natural capital. Therefore, a discussion will be presented, in the following, to thoroughly examine the environmental indicators to reduce their number.

According to (Dammak et al., 2024), multiple life cycle assessment studies indicate that the transportation stage is found to have a limited impact on the Eutrophication Potential (EP) of food groups. This is largely attributed to the low emissions of nitrogen compounds during transportation, estimated about 0.1 to 0.5 kg of nitrogen per tonne-kilometer (BE-IBGE, 2016), when compared to those generated during agricultural production. Moreover, nitrogen oxide (NO_x) emissions from road transport have been reported to continue decreasing beyond 2020. A 6.6% reduction in NO_x emissions between 2022 and 2023 is indicated in the Citepa report (Citepa, 2024). This ongoing reduction is attributed to advancements in vehicle technologies and stricter environmental regulations, which further minimize the transportation stage's contribution to EP.

Regarding the Potential Acidification (AP) indicator, it is generally considered to have a low to moderate impact on transportation companies compared to other environmental indicators. For example, a study by (CGDD, 2009) indicates that the AP factor for NO_x is 0.02174 kg/vkm, suggesting a relatively low environmental impact of the AP indicator on transportation companies. Since AP evaluates how pollutants contribute to acidification, it is more relevant to sectors like manufacturing that produce high levels of emissions. In contrast, transport companies are significantly impacted by GHG emissions and their associated climate change effects. Research indicates that transportation activities account for approximately 17% of global GHG emissions (Boston Consulting Group, 2021), underscoring the need for these companies to prioritize CO_2 emissions as a primary environmental concern. Furthermore, a systematic literature review has identified key indicators that are more appropriate for assessing the sustainability of urban freight transport, highlighting the importance of selecting indicators that align with operational realities (Buldeo et al., 2018). As a result, although the AP indicator might be useful in some situations, its direct application to transportation is still restricted.

Concerning the Fossil Fuel Depletion (FFD) indicator, it is demonstrated by research conducted by (Mankaa et al., 2024) that the depletion of abiotic resources, including fossil fuels, is considered a global issue, and no regionally differentiated characterization factors are developed. On the other hand, it is shown that the extraction and combustion of fossil fuels significantly contribute to greenhouse gas (GHG) emissions, and the environmental impacts of fossil fuel use are more accurately represented by indicators such as the Global Warming Potential (GWP), which is recognized as more precise in reflecting the ecological footprint of a company (Meyer, 2020). Consequently, the strong correlation between FFD and GWP is emphasized, highlighting the importance of using GWP to assess the energy sustainability of transportation companies (IPCC, 2021). Furthermore, it is stated by (CSS, 2024) that companies heavily reliant on fossil fuels, such as those in the transportation sector, can use GWP to effectively track and reduce their carbon footprint. In the European Union, for example, it is reported that road transport, including food logistics, accounts for approximately 22% of total GHG emissions in 2022 (Ian, 2024). For these reasons, the GWP indicator is retained, and the FFD indicator is removed from the initial list defined in D6.3.

For simplified dashboard visualization, the names of three indicators were adjusted without altering their informational content. First, "Degree of Satisfaction of Information Sharing Among Stakeholders" was changed to "Number of Stakeholders" based on expert feedback which highlighted the subjectivity and potential uncertainty in measuring satisfaction. Next, "Waste to Landfill" was shortened to "Waste" to provide a more comprehensive and global perspective, encompassing all types of waste rather than focusing solely on landfill-bound waste. Lastly, "Social Networks" was renamed to "Number of Followers on Social Media" for precision, ensuring the indicator reflects social media engagement.

Based on expert feedback, the water required for transportation of food products is very low compared to food processing thus providing a more accurate representation of water consumption within the AFSC. This viewpoint is supported by several studies (Hoehn, et al., 2021; Hoekstra, 2019). In (Caldeira et al., 2018), the authors analyzed the Water Scarcity Footprint (WSF) indicator for virgin and waste cooking oils. Their WSF analysis revealed that the cultivation stage is the primary source of water impacts, while the WSF of local transportation is negligible. The higher contribution of transportation observed for certain types of oils is associated with the use of heavy fuel oil in transoceanic ships. According to the conducted inventory, freshwater consumption for transportation and collection was 0.0014 m^3 per kg of waste cooking oil. For rapeseed oil in Spain, this consumption was about 0.0017 m^3 per kg, compared to 1.11 m^3 per kg during the cultivation stage. That's why; the WSF indicator is not included in the final list of relevant indicators regarding this actor.

Table 6 presents the finalized list of relevant sustainability indicators for transport companies.

Table 6 Final list of relevant sustainability indicators for transport companies

Capitals	Indicators	Unit
Natural	Global warming potential	kg CO_2 eq $\cdot$year^{-1}
	Waste	kg $\cdot$year^{-1}
Financial	Benefit-cost ratio	Dimensionless
Stakeholders	Company's earnings per share	TND (or Euros) /share
	Number of stakeholders	Number
Human	Labour productivity	Euros (or TND) $\cdot$h^{-1} $\cdot$year^{-1}
Relational	Number of deliveries per customer	Deliveries / Consumer
	Number of followers on the social media	Followers

3.2 Relevant Indicators for Critical Stakeholders

This section examines the predefined indicators for critical stakeholders, such as agri-food manufacturing, hotels, restaurants, hospitals, and supermarkets, in order to suggest a concise set of pertinent indicators. For such actor, indicators from the economic and environmental dimensions will be discussed. Regarding the economic dimension, it was suggested by the experts to combine the two indicators, "capacity of storage facilities" and "number of storage facilities," into a single one named "Average Storage Capacity per Facility." Furthermore, it was suggested that a single metric would allow for easier benchmarking against industry standards, which could drive continuous improvement in storage efficiency.

Let's verify the natural capital indicators, specifically those related to the "water theme." Initially, the Water Scarcity Footprint (WSF) was included in the first list of indicators to assess this theme. However, while the WSF highlights water scarcity, it provides limited context or detail about the underlying water use. Hoekstra et al. (Hoekstra et al., 2019) note that the WSF is less suitable for immediate evaluation because it relies heavily on regional context and can vary significantly based on local conditions.

According to (Hoekstra, 2015), the water footprint (WF) consists of both direct WF and indirect WF. Various studies have highlighted the importance of considering direct WF to assess the water category for natural capital, such as (Hoekstra, 2019) and (Mekonnen & Hoekstra, 2011). In fact, the data required to measure the indirect WF of stakeholders is complex, as it involves tracking water use through global supply chains, particularly from smallholders, as noted by (Hoekstra, 2015). Furthermore, the direct WF focuses on water incorporated into production processes, enabling stakeholders to track usage and identify efficiencies. It offers a clearer and more comprehensive assessment of water consumption throughout a product's or service's lifecycle, making it more practical for impact evaluation. For these reasons, the direct WF is used in the final list of indicators.

In collaboration with the LSR team (the French partner), the "Total demand of orders" indicator is added to the Stakeholder's capital because it captures the interactions between ASC actors.

The final list of selected indicators for critical stakeholders is as follows in Table 7.

Table 7 Final list of relevant sustainability indicators for critical stakeholders

Capitals	Indicators	Unit
Natural	Global warming potential	kg CO_2 eq ·year^{-1}
	Total energy consumption	Kwh/year
	Direct water footprint	m^3 H_2O-eq ·year^{-1}
	Ratio of waste	% ·year^{-1}
Financial	Benefit-cost ratio	Dimensionless
Material	Average storage capacity per facility	Tons per facility ·year^{-1}
Human	Labour productivity	Euros (or TND) ·h^{-1} ·year^{-1}
Stakeholders	Multi-stakeholders partnerships	Number
External Social	Number of new employees per year (seasonal and permanent)	Number ·year^{-1}

3.3 Relevant Indicators for Policy-Makers

The establishment of the final list of indicators for policy-makers is detailed below. The most important consideration for this actor, particularly in Tunisia, is water-related indicators. For this reason, four water indicators were included in the initial list, as defined in D6.3. This section will discuss which of these indicators will be retained in the final list. Firstly, according to (Tabari, 2020), the "Water Availability" (WA) and "Rainfall" indicators are correlated, and the first one is more representative of overall water resource management (Ehtasham et al., 2024). However, the indicators "Water Use Efficiency" (WUE) and "Water Stress" (WS) are reliant on WA in their mathematical formulas (FAO, 2023), which makes them correlated with WA. Additionally, according to the European Environment Agency (EEA, 2021), more thorough information about a region's water situation is provided by the WS than by the WA. Consequently, WS and WUE are regarded as pertinent indicators for the dashboard's water theme for policy-makers.

Regarding the emission category of natural capital, it should be noted that while national-level data is easily accessible in certain online databases, regional-level GHG emissions calculations are still difficult and frequently limited. Different studies such as (Elsoragaby et al., 2024) reveal the significant correlation between energy consumption and GHG emissions in agriculture, this relationship in particular practices. For instance, research on energy utilization in wetland rice cultivation found that fuel-related activities during tillage constituted 89% of total GHG emissions, amounting to 70 kg of CO_2 equivalent per hectare. According to another comprehensive study by (Flammini et al., 2021), the annual contribution of agricultural energy use to CO_2 equivalent was estimated to be 523 million tonnes, which rose to 1,029 million tonnes when electricity consumption was taken into account. Consequently, it was decided to maintain energy consumption as an indicator instead of GHG emissions in the final list of sustainability indicators.

Regarding the financial capital, one indicator, "% Total Projects Supported (public and private)," replaces both indicators: "% Projects Supported by the Government over a time period" and "% Projects Supported by Private Investment over a time period," reducing thus the total number of indicators. This indicator offers a thorough picture of overall support by combining public and private funding, which is crucial for assessing the effectiveness of funding initiatives.

For simplified dashboard visualization, the names of two indicators in the social dimension were adjusted without altering their informational content. Specifically, "Labor hours in the agriculture sector of the region" were shortened to "Regional labor hours required," and "(%) of Permanent Employees for the Agricultural activity per year" became "% of permanent employees."

The final list of selected indicators for policy-makers is presented in Table 8.

Table 8 Final list of relevant sustainability indicators for policy-makers

Capitals	Indicators	Unit
Natural	Cultivated land utilization index	Dimensionless
	Energy consumption for regional production	Kwh $\cdot$year^{-1}
	Water stress	% $\cdot$year^{-1}
	Water use efficiency	TND (or Euros)/m^3 $\cdot$year^{-1}
Financial	% Region Agricultural Added Value per year	TND (or Euros) $\cdot$year^{-1}
	Agricultural yield per year	ton $\cdot$ha^{-1} $\cdot$year^{-1}
Intellectual	% Total projects supported (public and private)	%TPS per last 3 years
	% of vulgarization program for smallholders over a time period	%VPS per last 3 years
Internal Social	% of permanent employees	% $\cdot$year^{-1}
	Regional labor hours required	hour $\cdot$year^{-1}

3.4 Relevant Indicators for Citizens

Similar to other actors in the AFSC, the number of natural capital indicators for citizens is substantial. On the one hand, this illustrates the significance of this capital, but on the other hand, it must be represented by a reduced yet significant number indicators. Consequently, two indicators that were previously defined, "% of purchases of organic or labeled/certified products" and "% of purchases of pesticide-free products," have been combined into a single one called "% of sustainable products purchased" in order to lessen cognitive overload on the citizen dashboard. The strong relationship between the agreement of an organic certification of an agri-food product and the use of pesticides well justifies this merger of indicators. Most organic labels, especially those certified by recognized organizations like the European label, impose strict restrictions on the use of synthetic pesticides (Calabro & Vieri, 2024).

Consequently, the percentage of organic product purchases generally includes the criterion of pesticide-free practices. This is well confirmed in studies showing that organically labeled products are primarily distinguished by their low levels of pesticide residues (Baudry et al., 2021).

To enhance dashboard visualization, the initial indicator "Number of participation in actions to raise awareness of sustainable development" was shortened and renamed as "Number of participants in sustainable awareness actions."

Similarly, the indicator "% of purchases of local products" was retained, whereas the indicator "% of purchases from local markets" was excluded for several reasons. The latter primarily reflects the point of sale, which may include non-local products, and does not necessarily support local agriculture. However, it should be emphasized that the distance products travel influences their carbon footprint. For instance, research by (Wadud et al., 2024) demonstrated that local sourcing reduces transportation distances and promotes local agriculture, which typically has a lower environmental impact compared to large-scale operations.

Regarding water-related indicators, two indicators exist: Water Used for domestic use (WU) and Water Footprint (WF). According to (Zhuo et al., 2020), there is a correlation between these two indicators. As mentioned in Section 3.2, WF includes both Direct Water Footprint (DWF) and Indirect Water Footprint (IWF). According to (Hoekstra et al., 2011), calculating the DWF for citizens is relatively simple, as it involves quantifying household water use. Moreover, this enhances the visibility of local water sustainability, helping citizens better understand the impact of their daily consumption habits. On the other hand, data collection for the IWF is far more complex due to the challenges of tracking water use throughout the supply chain, as highlighted in (Hoekstra, 2019; Hoekstra, 2015; Mekonnen & Hoekstra, 2011). Therefore, given these reasons, the platform focuses solely on the DWF for practical implementation rather than attempting to account for the entire WF.

Table 9 displays the final list of selected relevant indicators for citizens.

Table 9 Final list of relevant sustainability indicators for citizens

Capitals	Indicators	Unit
Natural	% of purchase of local products	% $\cdot$year^{-1}
	% of sustainable products purchase	% $\cdot$year^{-1}
	Carbon footprint	kg CO_2-eq .year^{-1}
	Direct water footprint	m^3 H_2O-eq $\cdot$year^{-1}
	Food waste	% $\cdot$year^{-1}
Financial	Cost food consumer	TND (or Euros) $\cdot$ year^{-1}
Internal Social	Number of participants in sustainable awareness actions	Number of actions per 3 years
External Social	Local availability of products	% $\cdot$year^{-1}

4 Conclusion

In this deliverable, the final lists of relevant multi-capital sustainability indicators, essential for optimizing the dashboard layer of the SMALLDERS platform, are presented for each AFSC actor. The first part outlined the fuzzy quality function deployment approach to derive the list of relevant sustainability indicators for smallholders. Then, an innovative sustainability index, based on the green total factor productivity method, is proposed for the final list of sustainability indicators for smallholders.

In the second part, the final lists of relevant indicators for transport companies, critical stakeholders, policy-makers, and citizens are presented. These lists are defined based on expert feedback as well as insights from the literature. Furthermore, it is worth emphasizing that these indicator lists were thoroughly validated and discussed with our French partner, given the strong interconnection between the dashboard and the decision-making layers. Project Technical Committee (PTC) meetings were also conducted to collaboratively discuss and validate these lists by considering their practical cases (testbeds). In addition, the finalized lists of indicators for each AFSC actor are aligned with the Sustainable Development Goals (SDGs). This alignment, as emphasized in D6.3, highlights their contribution to global sustainability objectives. Notably, the indicators align with SDG 1, SDG 2 and SDG 13. In D6.4, the importance of SDG 6 (Ensure Availability and Sustainable Management of Water and Sanitation) is well highlighted from the finding of a water indicator for all AFSC stakeholders' dashboards.

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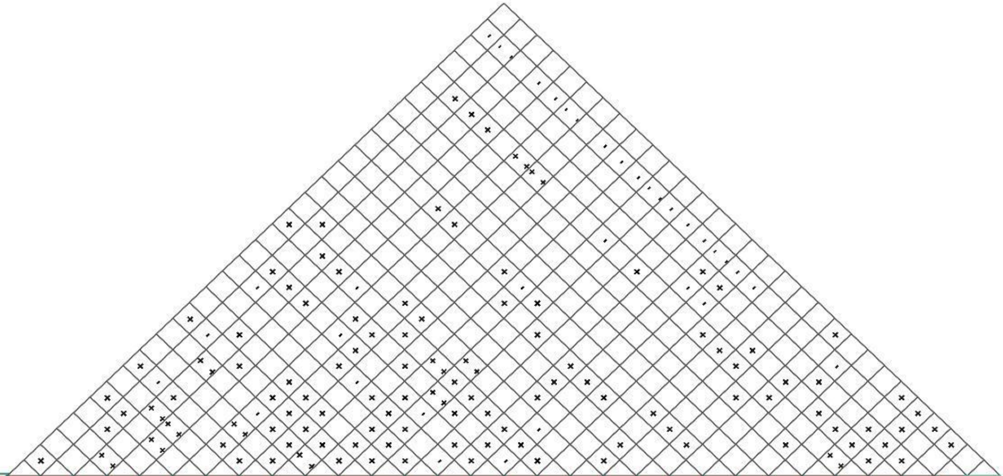
Appendices

Appendix 1 The Fuzzy House of Quality (HOQ) matrix by experts

Relationships	
7	Strong importance
5	Moderate importance
3	Low importance
1	Similar importance

Correlations	
++	Strong positive
+	Positive
-	Negative
--	Strong negative
	No correlation



Relative Weight	Capitals Importance Ranking	Capitals Rating	Capitals \ Indicators	Impact of over fertilization	Land Use Efficiency	Electrical Conductivity of Soil	Soil Moisture	Soil Color and Texture	Energy Use	Proportion of Renewable Energy	Impact of Acidification	Abiotic Depletion Potential	Impact on Climate Change	Water Use	Water Footprint	Post-harvest Loss	Income	Benefit-Cost Ratio	Costs of Cultivation and Storage	Land Value	Farm Size	Number of Heads	Level of Income	Gender Inclusion	Labour Productivity	Number of Agreements with stakeholders	Duration of Agreements	Number of Trainings	Number of Smart Technologies Used	Number of memberships in farmer's associations	Number of Participations in Collective Spaces	Crop Growth Duration	Farmer's connectivity to social networks
0.142	2	7.67	Financial	3	5	7	3	5	7	3	5	3	5	7	5	7	7	7	7	5	5	7	5	5	7	3	5	5	5	5	5	7	5
0.1296	3	7	Material	3	3	3	3	3	5	3	5	3	5	5	5	5	5	5	5	3	3	5	5	5	5	3	3	3	5	5	3	5	5
0.1173	6	6.33	Human	5	5	3	3	5	5	3	5	3	5	5	5	5	5	5	5	3	3	5	5	5	5	5	5	5	5	5	5	5	5
0.1296	3	7	Stakeholders	5	5	5	3	3	5	3	5	5	7	5	7	5	3	5	5	3	3	5	5	3	5	3	5	5	5	3	5	5	5
0.1296	3	7	Intellectual	5	5	5	3	5	5	3	5	3	5	5	5	5	3	5	5	3	3	5	3	3	5	5	3	5	7	7	5	5	5
0.0926	8	5	External Social	3	5	5	3	3	5	3	5	5	5	5	5	5	5	5	5	3	3	5	3	3	5	3	3	3	5	5	3	7	7
0.1049	7	5.67	Internal Social	3	5	5	3	3	5	3	3	3	5	5	5	5	5	5	5	3	3	5	5	3	5	5	5	5	5	5	3	5	5
0.1543	1	8.33	Natural	7	7	7	7	5	7	7	7	5	7	7	7	5	3	3	3	5	5	5	3	3	3	3	3	3	3	3	3	5	5
			Maximum Value	7	7	7	7	5	7	7	7	5	7	7	7	7	7	7	7	7	5	7	5	5	7	5	5	5	7	7	5	7	7
			Indicators importance	4,370	5,049	5,098	3,617	4,086	5,592	3,617	5,098	3,753	5,567	5,592	5,567	5,284	4,457	4,975	4,975	3,284	3,592	5,284	4,432	3,778	4,975	4,148	3,987	4,247	4,950	4,691	4,037	5.284	5,185
			Relative Weight	0,033	0,038	0,038	0,027	0,031	0,042	0,027	0,038	0,028	0,042	0,042	0,038	0,040	0,033	0,037	0,037	0,025	0,027	0,040	0,033	0,028	0,037	0,031	0,030	0,032	0,037	0,035	0,030	0,040	0.039
			Importance Ranking	18	7	7	26	20	1	26	7	24	3	1	7	4	16	11	11	29	26	4	16	24	11	20	22	19	14	15	22	4	6