HarvREStGreener Farming with RES

D4.2

HarvREStKPIs for agro-communities

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ABBREVIATIONS

AD	Anaerobic digestion
CEC	Cation Exchange Capacity
CF	Contamination Factor
CFE	Chloroform Fumigation–Extraction
CFI	Chloroform Fumigation–Incubation
CFU	Colony Forming Units
DM	Dry Mass
EC	Electrical Conductivity
FUE	Fertilizer Use Efficiency
GHG	Greenhouse Gas(es)
ICP	Inductively Coupled Plasma
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LAI	Leaf Area Index
M3	Mehlich 3 Method
MBC	Microbial Biomass Carbon
MBN	Microbial Biomass Nitrogen
PLI	Pollutant Load Index
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RES	Renewable Energy Sources
SI	Similarity Index
SLA	Specific Leaf Area
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
USDA	United States Department of Agriculture
WHC	Water-Holding Capacity

EXECUTIVE SUMMARY

This deliverable presents a structured framework of **Key Performance Indicators (KPIs)** designed to assess the integration of renewable energy sources (RES) within agro-communities under the HarvREST project. Given that agri-food systems contribute significantly to global energy consumption and greenhouse gas (GHG) emissions, the transition toward sustainable, low-carbon farming practices is both urgent and necessary. The HarvREST project addresses this challenge by promoting the adoption of RES technologies, such as solar, wind, and biomass, while ensuring alignment with agricultural productivity, environmental sustainability, and stakeholder needs.

The primary objective of this report is to define a coherent and practical set of agricultural and environmental KPIs that enable consistent monitoring and evaluation of RES impacts at the farm level. Building upon previous project deliverables, this work refines and consolidates indicators by linking them to identified impacts and mitigation strategies, ensuring relevance, reliability, and applicability across diverse farming systems.

The proposed KPI framework is divided into two main categories: **agricultural indicators (AG-KPI) and environmental indicators (EV-KPI)**.

- *Agricultural indicators* focus on crop health, nutrient use efficiency, and soil nutrient status. These include metrics such as critical plant and biomass density, leaf area index (LAI), and nutrient use efficiencies for nitrogen, phosphorus, and potassium. Additionally, soil fertility is assessed using indicators such as soil organic matter, total nitrogen, nitrates, and available phosphorus and potassium. Together, these KPIs provide insight into crop productivity and resource efficiency under RES-integrated conditions.
- *Environmental indicators* complement this assessment by addressing soil quality, biodiversity, and GHG emissions. Soil quality is evaluated through parameters such as soil texture, pH, electrical conductivity, biological activity, and water-holding capacity. These indicators capture the broader ecological impacts of RES technologies, including potential effects on soil structure, moisture, and microbial processes. Biodiversity and vegetation cover are assessed using similarity indices, while farm-level GHG emissions serve as a key metric to evaluate the overall climate impact of agricultural practices and energy integration.

Each KPI is supported by standardized measurement methods and interpretation guidelines, including threshold values where applicable. This ensures comparability across case studies and facilitates practical implementation by farmers, researchers, and policymakers. The framework is designed to function as both a monitoring tool and a decision-support instrument, enabling users to identify trade-offs, optimize resource use, and mitigate potential negative impacts associated with RES deployment.

In conclusion, this deliverable provides a comprehensive yet practical set of KPIs that support the evaluation of renewable energy integration in agro-communities. By combining agronomic and environmental perspectives, the framework contributes to informed decision-making and advances the transition toward more sustainable, resilient, and climate-neutral agricultural systems.

1. INTRODUCTION

1.1 Objectives and scope

Roughly 30% of the world's energy use is attributed to agri-food systems, with close to one-quarter consumed during the production phase alone, and about one-third of the anthropogenic greenhouse gas emissions. [1]. These figures underline the pressing need to lower both the environmental footprint and economic costs associated with energy use in agriculture. One promising pathway is the integration of renewable energy sources (RES), which can support the transition toward low-carbon and more sustainable farming systems. Nevertheless, adopting RES is not straightforward, as it involves navigating trade-offs, generating shared benefits, and accommodating the varied priorities of different stakeholders.

The **HarvREst** project was established to promote the uptake of renewable energy technologies in combination with sustainable agricultural practices, with the broader goal of reducing emissions in the agri-food sector. It adopts a comprehensive, multi-actor framework that considers **social, economic, environmental, technical, and regulatory dimensions to reconcile stakeholder needs**. The project is implemented through multiple case studies across Italy, Denmark, Spain, and Norway, where solutions such as solar panels, wind turbines, or biogas plants are co-developed, tested, and validated under real-life conditions.

In this framework, **Key Performance Indicators (KPIs)** play an essential role in assessing progress and measuring the effectiveness of RES integration into agro-communities. KPIs are measurable metrics used to evaluate performance and determine how successfully a process or system meets its objectives. Originally developed in business contexts, they are now widely used to guide decision-making and assess outcomes. Within agro-communities, KPIs can combine insights from agriculture, economics, environmental science, and social studies to support informed decisions and act as early warning tools against risks such as crop loss or depletion of shared resources. However, identifying the most appropriate indicators remains a complex task, as it requires connecting overarching project goals with the specific actions and interventions being implemented.

The objective of this deliverable is to **develop a coherent framework of agronomic (AG-KPI) and environmental Key Performance Indicators (EV-KPI)** to monitor and evaluate the sustainability, resilience, and productivity of farming systems within the HarvREst project.

1.2 Role of KPIs in monitoring sustainable and resilient farming systems

The transition towards **more sustainable and resilient agricultural systems** requires **reliable and measurable KPIs** capable of assessing farm performance from agronomic, environmental, and resource-efficiency perspectives. Within the HarvREst project, the proposed KPIs support the monitoring of farming systems associated with renewable energy integration, circular resource use, and sustainable agricultural management practices across the different use cases.

This deliverable focuses specifically on the development of agronomic and agro-environmental KPIs addressing **crop health, nutrient management, soil quality, biodiversity, pollution prevention, greenhouse gas emissions, and resource efficiency**. The indicators are intended to evaluate productivity, sustainability, and resilience while supporting the identification of **synergies and trade-offs** among different farming practices (Figure 1).

The proposed framework provides a coherent and reliable set of indicators, including standardized calculation methods and guidance for interpreting threshold values and monitoring farm performance over time. The applicability of the KPIs may vary depending on local climatic conditions, soil characteristics, topography, management practices, and the specific objectives of each HarvRESt use case. Therefore, the framework is designed to remain flexible and adaptable to different agricultural contexts and spatial scales.

The present deliverable, therefore, focuses on the integration of agronomic and agro-environmental indicators within a sustainability-oriented monitoring framework to support informed decision-making and the transition towards more sustainable farming systems.

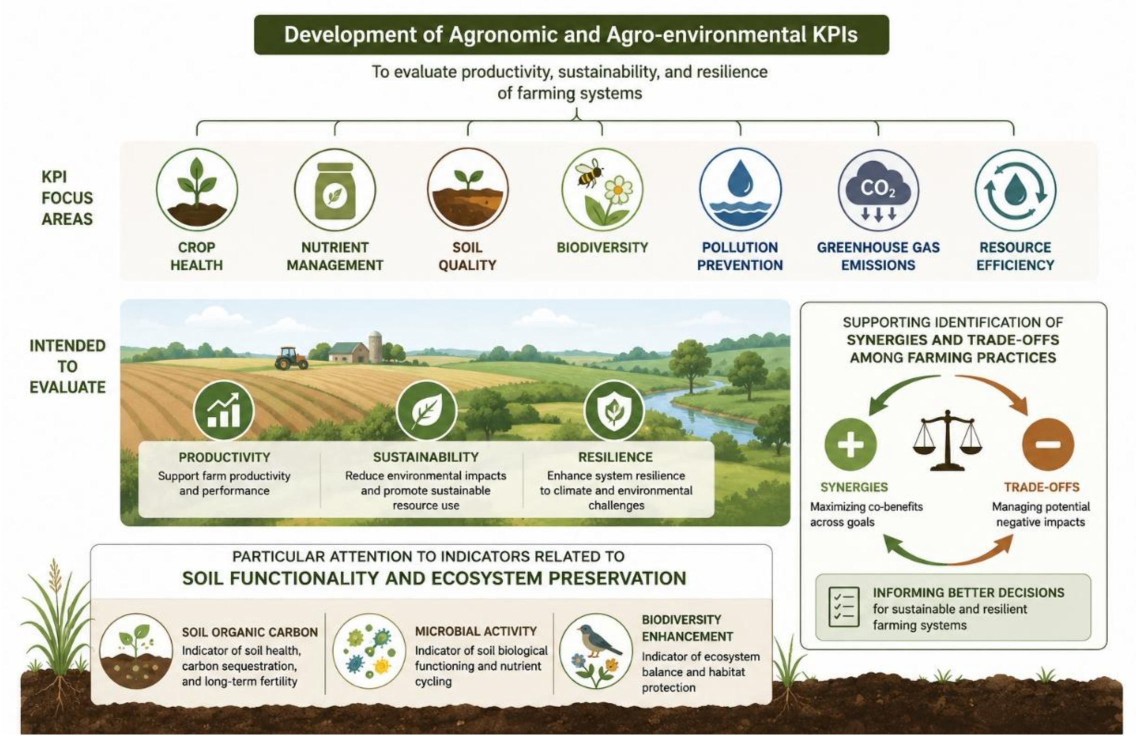

Figure 1. Development of Agronomic and Agro-environmental KPIs.

1.3 Link with Task 2.4 & 4.1

While HarvRESt also addresses renewable energy system performance, energy-related KPIs and technical RES monitoring indicators are covered in previous complementary deliverables. An earlier selection of KPIs was developed in task 2.4 and presented in the deliverable *"D2.2 HarvRESt monitoring KPIs for use cases",* which covered some agronomic, environmental, social, energy-related, and economic dimensions.

On the other hand, the deliverable *"D4.1 HarvRESt mitigation measures catalogue (first version)"* examined the potential impacts of RES integration within agro-communities and associated mitigation strategies, linking KPIs (from the deliverable *"D2.2 HarvRESt monitoring KPIs for use cases")* to each identified impact, to highlight overlaps and gaps.

In the present work, agronomical and environmental KPIs were designed to monitor RES impact in every farm-RES system, independently of their context. To this aim, this work has been co-developed with the deliverable *"D4.5 HarvRESt mitigation measures catalogue (final version)"* to consolidate a list of impacts and mitigation measures linked to both performative-KPIs (from D2.2) and impact-KPIs (this work). Co-development with D4.5 allowed to refine the impact-KPI selection by addressing missing elements, removing redundancies and identifying common impacts shared among RES. Therefore, the present KPIs are adapted to monitor the agronomical and environmental impacts of integrating any RES system in all farms and local contexts.

2. FRAMEWORK FOR KPI SELECTION AND MONITORING

2.1 Methodological approach for KPI selection and data availability

The proposed indicators were selected to ensure applicability across a broad range of farming systems and use cases represented within the project. For this reason, no crop-specific KPIs were included, and preference was given to indicators that can be applied under different agricultural, climatic, and management conditions.

The selection of KPIs was based on several criteria, including their **relevance to project objectives, applicability across different farming systems, data availability, scientific robustness, and capacity to reflect changes associated with sustainable agricultural practices**. Particular attention was given to indicators related to crop productivity, nutrient management, soil quality, biodiversity, pollution prevention, and greenhouse gas emissions. Existing sustainability assessment methodologies and soil quality frameworks, including the CWA 17898:2022 methodology, were considered during the development of the KPI framework (Figure 2).

To support their application, each KPI is accompanied by standardized calculation methods, units of measurement, and guidance for interpreting threshold values.

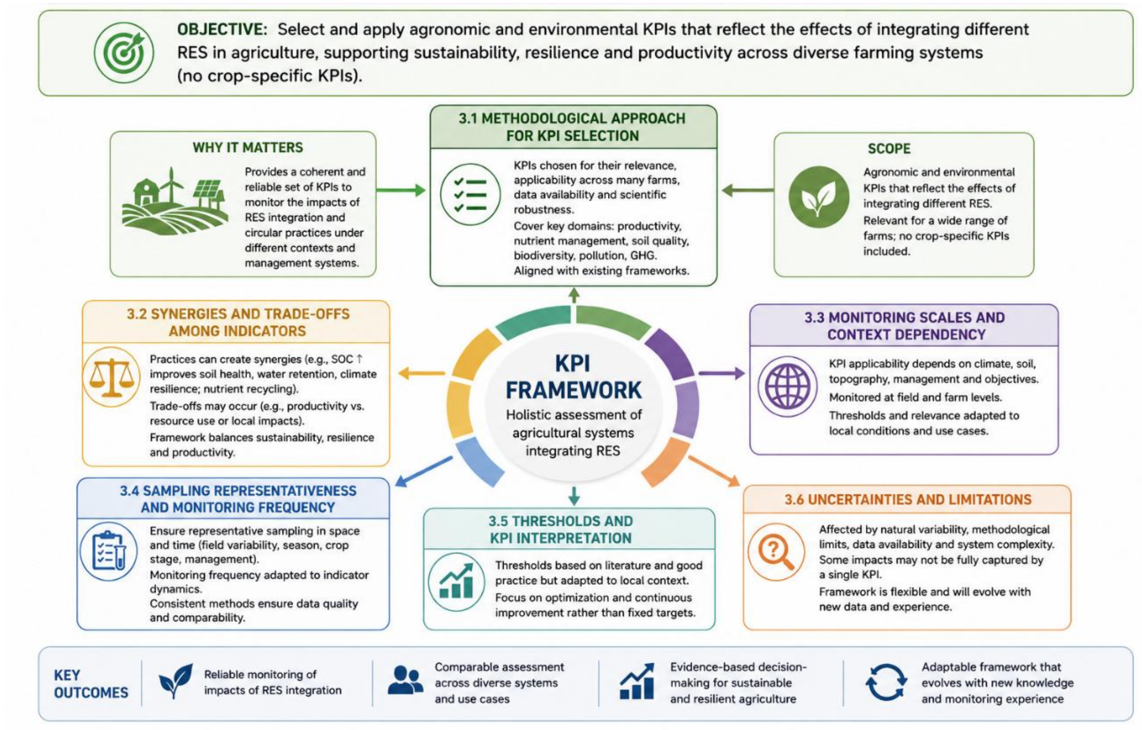

Figure 2. Methodological framework for KPI selection

2.2 Synergies and trade-offs of RES integration in agricultural systems

Agricultural systems integrating RES and circular resource management practices may generate both synergies and trade-offs affecting productivity, environmental sustainability, resource efficiency, and ecosystem preservation. The proposed KPIs have been selected to monitor these effects and provide a comprehensive assessment of farm performance.

Several agricultural practices implemented within the HarvREStuse cases may simultaneously generate multiple environmental and agronomic benefits. For example, practices aimed at increasing soil organic carbon may improve soil fertility, microbial activity, water retention capacity, and climate resilience. Similarly, the use of digestate derived from biogas production may contribute to nutrient recycling while reducing dependency on synthetic fertilizers, increasing the sustainability of farms.

At the same time, some practices may involve trade-offs between productivity and environmental impacts. For instance, photovoltaic panels influence local microclimatic conditions, improving crop resilience under extreme weather conditions, but with an impact on soil microorganisms and the surrounding biodiversity, making farm sustainability uncertain.

The proposed framework aims to support **a holistic interpretation of RES impacts by considering interactions among indicators and balancing sustainability, climate resilience, biodiversity, and farm productivity objectives**.

2.3 Monitoring scales and context dependency

Methodology for monitoring RES impact depends on the scale and context of the RES installation. The HarvRESt project studies the integration of **RES installations within a farm or a local system of collaborative farms**. Therefore, not all-scales RES installations were considered in this work to monitor their impact. For instance, big-scale dams for hydropower generation are not a technology to be applied within a farm or a system of farms. Conversely, big-scale wind turbines can be installed within the territory of large farms, whose impacts can be monitored on the farm.

Besides, the context of the RES installations in this work is always within the agro-forestry sector, which occupies mostly **agricultural lands in rural areas**. These lands are generally surrounded by natural spaces rather than urban spaces, with subsequent impacts on the environment and biodiversity. For this reason, the focus of this work is also on environmental KPIs, and not only agronomic KPIs.

Consequently, developed KPIs will monitor the impact of RES installations (mostly small and medium scale) on farms and local systems in rural areas.

2.4 Monitoring procedure and frequency

To support reliable monitoring and comparability of results, the framework considers general methodological aspects related to sampling representativeness. While detailed methodologies are provided within each KPI description, common principles regarding measurement quality and temporal variability are considered throughout the framework. Furthermore, many KPIs cannot be measured by farmers; therefore, whether external laboratory services are absolutely required to measure each KPI is indicated in Table 1.

Sampling procedures should ensure that the collected data adequately represent the monitored field or farming system. This includes consideration of spatial variability within fields, seasonal fluctuations, crop development stages, and management practices that may influence indicator values.

2.5 General approach for thresholds and KPI interpretation

The framework considers the use of threshold values, reference ranges, and optimization approaches for selected indicators.

Threshold values included within the KPI descriptions are based on literature references, existing sustainability frameworks, or commonly accepted agronomic practices whenever available. However, these thresholds should not necessarily be interpreted as fixed targets, since optimal values may vary depending on local environmental conditions, farming systems, and management objectives.

In several cases, the interpretation of KPIs should focus on optimization trends rather than strict compliance with predefined threshold values. For example, nitrogen use efficiencies above 40% is an agronomic practice generally accepted, but tend to 100% is optimal for both agronomic and environmental purposes.

2.6 Uncertainties and limitations

Uncertainties and limitations associated with agricultural and environmental monitoring are acknowledged within the proposed framework. Biological variability, climatic fluctuations, spatial heterogeneity, and differences in management practices may influence the interpretation of KPIs and the comparability of results among use cases. Some indicators may also be affected by methodological limitations related to sampling procedures, analytical methods, temporal variability, or data availability. In addition, the complexity of agricultural systems means that some environmental impacts or ecosystem interactions may not be fully captured by a single indicator.

Since the framework aims to remain broadly applicable across different agricultural systems and use cases, some crop- or site-specific dynamics may not be fully represented within the selected KPI set. Consequently, **the proposed KPI framework should be considered as a flexible and evolving approach** that can be progressively refined as additional data, monitoring experience, and scientific knowledge become available throughout the implementation of the HarvRESt project.

3. KPIS FOR AGRO-COMMUNITIES

¡Error! No se encuentra el origen de la referencia. shows the selected Agricultural and Environmental KPIs, which have been referred to a specific code.

Table 1. Agricultural and Environmental KPIs

KPI Code	KPI Name	Lab services required
Agricultural indicators		
Crop Health		
KPI.AG.01.01	Critical plant density	No
KPI.AG.01.02	Critical biomass density	No
KPI.AG.01.03	Reduction of solar radiation and leaf area index	No
KPI.AG.01.04	Crop yield	No
KPI.AG.01.05	Nutrients in leaves	Yes
Fertilizer Use Efficiency		
KPI.AG.02.01	N-Fertilizer use efficiency	Yes
KPI.AG.02.02	P-Fertilizer use efficiency	Yes
KPI.AG.02.03	K-Fertilizer use efficiency	Yes
Soil C and Nutrient Status		
KPI.AG.03.01	Soil organic matter (SOM) and carbon (SOC)	Yes
KPI.AG.03.02	Total N	Yes
KPI.AG.03.03	Nitrates	Yes
KPI.AG.03.04	Available P	Yes
KPI.AG.03.05	Available K	Yes
Environmental indicators		
Soil Quality Impact		
KPI.EV.01.01	Soil texture	Optional
KPI.EV.01.02	Soil pH	Optional
KPI.EV.01.03	Electric conductivity (EC)	Yes
KPI.EV.01.04	Soil microbiological activity	Yes
KPI.EV.01.05	Soil water-holding capacity (WHC) and water content	Optional
Biodiversity and pollution		
KPI.EV.02.01	Vegetation diversity and cover	No
KPI.EV.02.02	Weed-insect pollinator indicator	No
KPI.EV.02.03	Soil emissions	Yes
KPI.EV.02.04	Heavy metal pollution	Yes
KPI.EV.02.05	Pathogen contamination	Yes
KPI.EV.02.06	Microplastic contamination	Yes

3.1 Agricultural indicators

3.1.1 *Crop Health*

The limits of a healthy crop can be determined by several parameters, including its biomass yield, the number of plants per hectare of land or its capacity to use the solar radiation.

An excessive plantation leads to a reduction of resource availability, which negatively affects crop yields. Crop yield can be measured as the amount of product (fruit, grains, leaf, etc) per hectare, but the most general crop yield indicator is the biomass yield or density. Biomass density is directly related to the characteristics of the plant and the crop surface; hence, it is a good reference for the average crop health. Besides, plant growth is highly related to its capacity to capture solar radiation. Therefore, the KPIs chosen to determine critical thresholds of crop yield can be checked in Table 2.

Table 2. KPIs selected to determine crop health

KPI code	KPI name	Unit
KPI.AG.01.01	Critical plant density	Plants/m^2
KPI.AG.01.02	Critical biomass density	Kg biomass/m^2
KPI.AG.01.03	Reduction of solar radiation and leaf area index	%
KPI.AG.01.04	Crop yield	Kg/ha
KPI.AG.01.05	Nutrients in leaves	unitless

In relation to RES, these KPIs can show how crop yield can be affected by the implementation of solar panels, wind turbines or even the use of biomass for bioenergy production. Considering the surface necessary for these technologies, it can provide the expected crop yields based on the free surface and/or the shared surface (if crop characteristics under these conditions are known).

KPI.AG.01.01 Critical plant density

Thresholds for this KPI depend on the type of plant, especially on its **size (M) [kg/plant].** According to Deng et al. (2012), a crop should not have more plants than the **critical plant density (N_{crit}) [plants/m^2]**, which for most of the plants it has the following relation with M:

Equation 1. Critical plant density.

$$log_{10}(N_{crit}) = -(0.78 \pm 0.01) * log_{10}(M)$$

E.g., considering a crop with an average plant size of 1g (0.001 kg/plant), the N_{crit} would be 204 - 234 plants/m^2.

KPI.AG.01.02 Critical biomass density

Another index of crop health is the **critical biomass density (W) [kg/m^2]**, which for most of the plants it has the following relation with M [2]:

Equation 2. Critical biomass density.

$$log_{10}(W) = -(0.26 \pm 0.01) * log_{10}(M)$$

For instance, considering the same crop with an average plant size of 1g (0.001 kg/plant), the W would be 5.62 – 6.46 kg biomass/m^2. For a 1g/plant, having biomass density (W) out of that range means there is some crop deficiency. Nonetheless, these values are approximations; more accurate values can be obtained using crop-specific equations that can be found in Deng et al. (2012).

KPI.AG.01.03 Reduction of solar radiation and leaf area index

Integration of some RES technologies (i.e., photovoltaics) might produce shaded areas, which can reduce solar radiation in crops below and surrounding the Agro-PVs. The leaf area index (LAI) is an indicator that correlates plant growth or health with its use of the solar radiation. Biologists and agronomists use LAI to estimate yield potential, water use efficiency, mineral nutrition efficiency and damages caused by pests and diseases, in addition to plant growth and solar radiation efficiency [3]. The specific leaf area (SLA) is determined through measurements of the area of single leaves (A) divided by the corresponding dry mass (DM_{leaves}). SLA depends on the plant species, development stage, seasonality and site conditions. Then, the LAI is this SLA multiplied by the total dry mass of the crop (DM_{leaf}) and divided by the crop surface (S):

Equation 3. Leaf area index (LAI).

$$LAI = \frac{\left(\frac{A}{DM_{leaves}}\right) * DM_{leaf}}{S}$$

The percentage of shaded-crops LAI against sun-crops LAI can serve as an indicator of the impact of solar reduction by RES technologies. LAI values of **crops under the sun** can vary across a whole year, from **1.8 to 2.8 m^2/m^2**. In half-shaded crops (25-73% solar reduction), LAI values range from 1.2 to 1.9 m^2/m^2, which is a 67% of the LAI in sun crops. For shaded crops (65-83% solar reduction), LAI values range from 0.6 to 0.9 m^2/m^2, this is a 30% of LAI in sun crops [4]. In the mentioned study, biomass did not develop properly under shaded and half-shaded conditions; therefore, shadows produced by RES technologies **should not reduce solar radiation by more than a 30%**, to avoid LAI values below 70% of the LAI in sun crops.

KPI.AG.01.04 Crop yield

The crop yield is the most traditional measurement applied by farmers to track the crop performance. It is a measurement of the amount of agricultural production harvested per unit of land area. The agricultural production is the number of parts of a harvested crop that is the main economic product. For example, in a vineyard, it is the number of grapes, not the whole plant nor the residual leaves. Crop yield is highly dependent on the crop type, environmental conditions and management practices, hence, in this KPI, general thresholds cannot be provided. Instead, examples of experienced crop yields are provided with standard deviations: wheat crops can produce on average 4000 ± 300 kg/ha in a year, whereas vineyards can produce 750 ± 100 kg/ha in the same period.

KPI.AG.01.05 Nutrients in leaves

Leaves are an important and representative part of the plant, whose analysis can provide valuable information about the plant nutrient status. Analysing nutrient concentrations in leaves serve **to diagnose problems** of scarcity, bad management, water issues and fertilization requirements [5]. For this evaluation, the main nutrients to study are nitrogen, phosphorus, potassium, calcium and magnesium. The optimal range of these nutrients is crop specific, but some **nutrient ratios are of special interest** and can be standardized for most crops (Table 3).

Table 3. Optimal ratios of nutrients in leaves to evaluate plant status [5].

Ratio	Optimal range
N/P	9 – 11
K/Ca	0.7 – 1.0
K/Mg	3 – 6

The **concentration** of each of these nutrients is calculated **as a dry weight percent**; this is the number of milligrams of a nutrient that is in 100 mg of dry matter. There are different methods to analyse several nutrients in leaves. Here, to analyse all nutrients of interest at once, acid digestion of leaves and subsequent analysis in **Atomic Absorption Spectrometer** is recommended [6]. For this, a representative number of leaves from a representative number of plants need to be sampled, the amount of sample depends on the season, crop type and age [7].

These ratios are important to maintain the nutrient balance and physiology of plants. For instance, K competes against Ca and Mg to be up taken by the plant because they share the same absorption mechanism, therefore, an imbalance of K/Ca or K/Mg in soil will lead to imbalances in the plant and subsequent diseases [5]. On the other hand, high N/P means high N content, that might be related to nitrate content. Excessive nitrates in plants can be toxic, and, in the case of food/feed purposes, its content is regulated (EC No 1881/2006) [5]. Therefore, leaf analysis allows to identify these imbalances, to tackle them applying mitigation measures.

3.1.2 *Fertilizer Use Efficiency*

Fertilizer use efficiency (FUE) measures the nutrient recycling from waste in farms and its use as fertilizer in crops. This can be, for instances, the case of biogas plants in farms that recycle the produced digestate as fertilizer. Three main nutrients are considered when fertilization, nitrogen (N), phosphorus (P) and potassium (K), hence three KPIs are used to determine specific FUEs (Table 4).

Table 4. KPIs selected to determine fertilizer use efficiency

KPI code	KPI name	Unit
KPI.AG.02.01	N-Fertilizer use efficiency	%
KPI.AG.02.02	P-Fertilizer use efficiency	%
KPI.AG.02.03	K-Fertilizer use efficiency	%

FUE is calculated as the percentage of nutrients (N, P or K) from fertilization that is taken by the crop biomass [8]:

Equation 4. Fertilizer use efficiency.

$$FUE = 100 * \frac{(Nutrient\ uptake_{fertilized} - Nutrient\ uptake_{unfertilized})}{Nutrient\ applied}$$

Any positive FUE value means improvement compared to unfertilized crops. Generally, it is considered a good fertilization when FUE reaches values such as [9]:

KPI.AG.02.01 N-Fertilizer use efficiency	FUE_N = Between 40 and 50% for nitrogen
KPI.AG.02.02 P-Fertilizer use efficiency	FUE_P = Between 70 and 80% for phosphorus
KPI.AG.02.03 K-Fertilizer use efficiency	FUE_K = Between 60 and 70% for potassium

However, these values mean there is nutrient loss yet (the difference of up to 100% FUE). Optimization of FUE consists of supplying all nutrients while applying a minimal amount of fertilizer, to reach the closest FUE value to 100%. An optimization approach should be considered rather than staying on traditionally accepted FUE values.

3.1.3 *Soil Carbon and Nutrient Status*

The nutrient status of soil is essential to know the soil fertility and its deficiencies. Since the main application of digestate (produced in biogas plants) is as fertilizer, it is important to measure its impact in the soil fertility. The following KPIs measure main soil nutrients such as the organic carbon and organic matter, along with available N, P, K and total N (Table 5).

Table 5. KPIs selected to determine soil carbon and nutrient status

KPI code	KPI name	Unit
KPI.AG.03.01	Soil organic matter (SOM) and carbon (SOC)	%
KPI.AG.03.02	Total N	%
KPI.AG.03.03	Nitrates	mg/kg
KPI.AG.03.04	Available P	mg/kg
KPI.AG.03.05	Available K	mg/kg

KPI.AG.03.01 Soil organic matter (SOM) and carbon (SOC)

Soil organic matter (SOM) is the main source of nutrients for soil microorganisms, which are key in the soil carbon and nitrogen cycling and serve as biological control of plant diseases. Moreover, SOM has an impact on several physical properties of soil, such as its porosity, water holding capacity, moisture and others [3].

Soil organic carbon (SOC) is the major fraction of SOM, which is determined by the oxidation with sulfochromic standard method ISO-14235 [10]. This method has been recently banned due to its associated hazards. SOC can be estimated from SOM values applying the **"Van Bemmelen factor" of 1.724**, which has been used for many years, and it assumes that SOM contains 58% of organic carbon.

The literature indicates that the proportion of organic C in organic matter for a range of soils is highly variable, although the Van Bemmelen factor is well applied in most arable soils. Nonetheless, several pieces of information about soil health can be deduced from SOM, which is the volatile solids in soil as a percentage by dry weight, measured through the standard method APHA-2540 [11] (Table 6).

Table 6. Interpretation of soil organic matter (SOM) and carbon (SOC) [5]. *SOC is based on the SOM interpretation, converting values through the Van Bemmelen factor.

SOM (%)	SOC (%) *	Interpretation
< 1	< 0.58	Very low
1 - 2	0.58 – 1.16	Low
2 - 3	1.16 – 1.74	Optimal
3 - 4	1.74 – 2.32	High
> 4	> 2.32	Very high

KPI.AG.03.02 Total N

Nitrogen present in soil can be classified either as organic (being part of plants, microorganisms and other organic matter) or mineral (NO_2, NO_3 and NH_4). Mineral sources count for 5 – 10% of the total N in soil, and it is readily available for plant uptake. Organic sources are not readily available for plants, and need to be transformed into mineral nitrogen by nitrifier and denitrifier bacteria [3].

"Total N" in soil is usually measured through the **Kjeldahl method**; however, this method determines organic nitrogen and ammonium nitrogen, and it does not account for nitrate or nitrite nitrogen unless a modified procedure is used. Hence, nitrates are measured separately to extract more information; this is developed in the following section KPI.AG.03.03 Nitrates.

The interpretation of total N is traditionally provided for the Kjeldahl method (Table 7).

Table 7. Interpretation of Kjeldahl nitrogen in soil [5]

Total N (%)	Interpretation
<0.07	Very low
0.07 - 0.10	Low
0.10 - 0.15	Average
0.15 - 0.20	High
>0.20	Very high

Total N can be interpreted together with SOC as **SOC/TN ratio**, which indicates the potential of soil to release N to the atmosphere. Soils with low microbial activity have SOC/TN ratios above 12, potentially releasing N, whereas soils with too high microbial activity have ratios below 9, fixing too much N into organic matter, which is not plant available. A correct N release occurs when SOC/TN is between 10 and 12 [3].

KPI.AG.03.03 Nitrates

The content of nitrates in soil is the most important parameter **to consider before applying nitrogen fertilization**, since nitrates are promptly used by plants. The content of nitrates depends on several factors: the mineralization of organic nitrogen, the presence of ions, leaching, weather conditions, etc. Nitrates can be measured through ionic chromatography. Nitrates content in soil can be between 5 and 80 mg/kg (Table 8).

Table 8. Interpretation of content of N from nitrates in soil [5].

N from NO_3 (mg N-NO_3/kg)	Interpretation
<10	Low
10 - 15	Lightly low
15 - 20	Average
20 - 25	Optimal
>25	High

Nitrate values equal or greater than optimal (20 mg NO_3/kg) indicate that the soil does not need N fertilization. Moreover, nitrates are highly soluble; thus, increasing the content of nitrates has high **leaching risks**, which leads to water pollution. In addition, when nitrates are accumulated or transformed into NO or NO_2, it can cause greenhouse gas emissions [3].

KPI.AG.03.04 Available P

Phosphorus (P) is an essential element for the life cycle of plants; it represents only a 2 to 3% weight of the soil, and it is strongly bound to cations in the form of phosphates. These phosphates are present in three fractions in soil: soluble (available for plants), labile form and non-labile form [3]. The available P in the soil solution is not very mobile and accumulates in soil; hence, **P-fertilizers** need to be buried close to the roots for a correct application and to minimize water pollution risks. The most extended method to measure available P is the **"Olsen method"** [12] (Table 9).

Table 9. Interpretation of available P in soil (Olsen method) [5].

Available P (mg/kg)	Interpretation
<12	Low
12 - 24	Average
24 - 36	Optimal
36 - 80	High
>80	Very high

Another well extended colorimetric method to measure available P is the "Mehlich 3 method" (M3), which has a good correlation to Olsen on alkaline soils (R_2 = 0.918). When M3 extracts are analysed in the inductively coupled plasma emission spectroscopy (ICP), it allows to measure potassium and several macronutrients at once, however, P values are higher because the ICP measures all P forms [3]. Several other methods have been tested to measure the available P in soil [13], however all of them are qualitative, since none of the methods can determine exactly the amount of available P, only relative values.

KPI.AG.03.05 Available K

Potassium (K) has an important role in plants, such as the development of cellulose and lignin (giving structural strength to plants), regulation of cell-water regulation and the electrical balance. Therefore, plants have a high K demand. Unlike N and P, K does not form organic compounds; it is in the form of salts, which can be: **K in the soil solution (0.1 – 0.2% of total K), exchangeable K (1 – 2% of total K)**, fixed K (1 – 10% of total K) or mineral (90 – 98% of total K) [14]. Only K in soil solution and exchangeable K are readily available for plants. Available K is measured through **extraction with ammonium acetate** (Table 10).

Table 10. Interpretation of available K [5].

K (mg/kg)	Interpretation
<125	Low
125 - 175	Average
175 - 250	Optimal
250 - 350	High
>350	Very high

Both excess and deficit of K in plants lead to quality problems of the crop production. As the phosphorus, K is not very mobile and it can get accumulated, hence **K-fertilizers** need to be buried close to the roots to enhance its adsorption. Besides, organic matter retains water and, thus, available K, this helps to avoid its transformation into non-available K forms [9].

3.2 Environmental indicators

3.2.1 *Soil Quality Impact*

The following KPIs measure aspects of soil health beyond its nutrient status, that was developed in the previous sections as agronomic indicators. These measurements are essential for soil characterization and to interpret the impact of agricultural practices and/or the impact of RES into soil quality. The implementation of technologies such as solar panels or wind turbines can have an important impact on soil compaction and moisture, which can also affect, for example, the soil's biological activity and pH (Table 11).

Table 11. KPIs selected to determine soil quality impact

KPI code	KPI name	Unit
KPI.EV.01.01	Soil texture	%
KPI.EV.01.02	Soil pH	pH
KPI.EV.01.03	Electric conductivity (EC)	dS/m
KPI.EV.01.04	Soil biological activity	µg/g
KPI.EV.01.05	Soil water-holding capacity (WHC) and water content	%

KPI.EV.01.01 Soil texture

Soil texture is determined through the **"Bouyoucos method"**, based on the density of each soil fraction. Three fractions are differentiated: sand (composed of granules of 0.05-2 mm diameter), silt (0.02-0.05 mm) and clay (<0.02 mm). The Bouyoucos method calculates the proportion of each fraction within the soil, this determines different textures which are described in the diagram of the United States' Department of Agriculture (USDA), represented in Figure 3.

Each soil texture has associated characteristics [9], such as:

- Clay (> 30% clay): strong water and nutrient retention, this leads to puddles forming, to have bad soil aeration, difficult drainage and dense soil.
- Sand (< 10% clay): low moisture, tend to dry, low fertility but good aeration.
- Loam (10 – 30% clay): good water and nutrient retention, and good aeration.

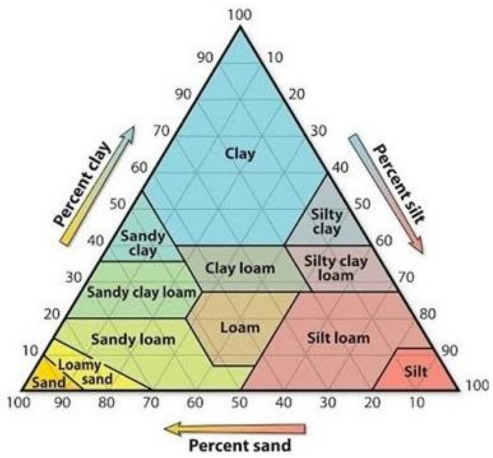

Figure 3. USDA diagram for soil textures

The texture should be a permanent property of the soil, it has a direct relationship with the aeration of soil, risk of compaction and drainage. Hence, soil texture determines the type of crops that can grow on them.

KPI.EV.01.02 Soil pH

The pH impacts the solubility of different minerals in soil, the availability of certain elements (Figure 4**¡Error! No se encuentra el origen de la referencia.**), the plant growth and microbial activity [9]:

- **Basic soils** (pH > 7.5) have a high content on Ca^{2+}, Mg^{2+}, carbonates and sulphates. Carbonate content limits assimilation of Fe^{2+}, Mn^{2+}, Zn^{2+} and phosphorus which precipitate into insoluble forms. In addition, the presence of sodium carbonates impermeabilizes soil, this maintains pH stable within the basic range. An example of basic soils are limestone soils. This pH is more suitable for cereal crops.
- **Neutral soils** (pH = 6.5 – 7.5) are optimal for most of crops, but especially for fruit crops. This pH enhances the assimilation of nutrients.
- **Acid soils** (pH < 6.5) are unfavourable for root growth and the microbial activity, the content of Ca^{2+}, Mg^{2+} and K^{+} is low, and, as for basic soils, phosphorus precipitates into insoluble forms that reduces its assimilation. Vegetables are adapted to a wider range of pH (from 5.5 to 7.8), making them suitable to culture in both acid and neutral soils.

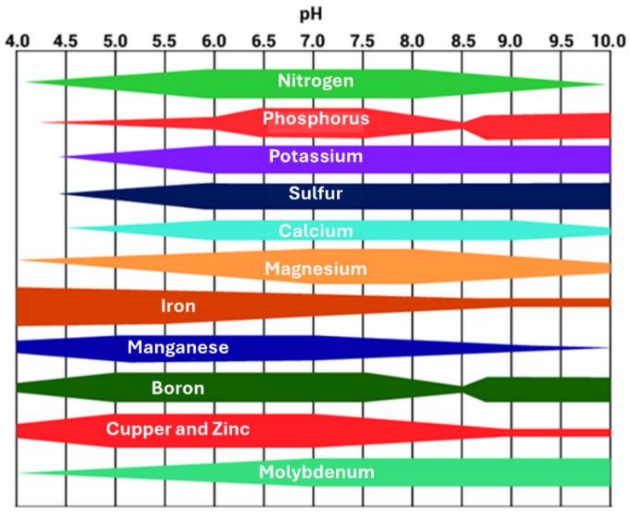

Figure 4. Element availability depending on soil pH. Image modified from J. Z. Castellanos et al. (2000)

Changes in soil pH can occur, but it usually has a temporal effect as the presence of carbonates has a buffer effect that avoid permanents changes. For this reason, calcareous soils are especially resistant to pH changes. Some agricultural practices can change the soil pH temporarily to improve nutrient assimilation. For instance, the application of some N-fertilisers produces micro-acidifications due to the presence of nitrification inhibitors that help to slow the N release [5].

KPI.EV.01.03 Electric conductivity (EC)

The electric conductivity of soil is an indicator of **soil salinity**, which has an important impact on plant physiology. EC is highly related to the soil texture, soil cation exchange capacity (CEC), temperature, pH and SOM. For instance, sandy soils have low EC, whereas clays have high EC. Soils with medium EC and medium water holding capacity are the most productive [9].

EC can be determined through the standardized method ISO-11265 [15]. This method requires some time, so laboratories also offer a fast diagnostic based on the presence of salts in a soil solution (10 g soil : 50 mL water) ($EC_{1:5}$) [9]. The interpretation of EC and salinity may depend highly on the sensitivity of the crop species (Table 12).

Table 12. Interpretation of electric conductivity with examples of tolerant crops [3].

EC (dS/m)	$EC_{1:5}$ (dS/m)	Interpretation	Example crop
< 2	< 0.35	No salty	Bean
2 – 4	0.35 – 0.65	Lightly salty	Corn
4 – 8	0.65 – 1.15	Salty	Wheat
> 8	> 1.15	Very salty	Barley

The EC can be affected by agricultural practices such as the type of water and the amount of water used, the application of organic amendments and drainage. In a RES-integrated system in farms, the impact on EC can potentially come from the water of washing solar panels or from the application of digestate as fertilizer. Since changes in EC can negatively affect crops and soil health, this parameter should be frequently measured when integration of RES into the farm.

KPI.EV.01.04 Soil microbiological activity

Microorganisms such as bacteria and fungi, together with micro- and macrofauna, play a central role in carbon and nitrogen cycling within soils. Soil animals first break down organic material, after which microbes further decompose the resulting carbon and nitrogen compounds. To assess soil health, standardized approaches typically estimate microbial activity and biomass indirectly, through microbial respiration [16]. This is a relative method, useful to track changes within the same field, but not to compare between different fields that might have a different microbial community and biomass. On the other hand, measuring microbial activity, community and biomass through direct methods provides more information, which is more accurate and allows to compare different ecosystems. However, direct methods are also more expensive and less accessible; they consist primarily of DNA sequencing and quantification, and enzymatic activity measurements [3]. Therefore, this deliverable proposes to measure microbial activity through indirect methods, as a good-enough, cost-effective solution to track RES impact within a soil system.

The most widely used technique to measure biological activity indirectly is the **chloroform fumigation standard method** ISO-14240 [17]. This technic captures a large proportion of soil microbial biomass carbon (MBC) and nitrogen (MBN), both from living and dead biomass. Although, certain organisms, such as spores, may resist the fumigation process [16]. Chloroform fumigation includes two main approaches: chloroform fumigation–incubation (CFI) and chloroform fumigation–extraction (CFE) [18]. In both methods, exposure to chloroform vapor eliminates soil microorganisms. The resulting microbial biomass is then estimated either by measuring the CO_2/N_2 released during a defined incubation period (CFI) or by extracting the soil immediately after fumigation and quantifying the extractable C or N (CFE). Reported MBC values typically range between 60 and 1400 µg MBC/g soil, representing 1 – 5% of the soil organic carbon [18], [19] (Table 13). Although these measurements are indicators of microbial activity, it does not allow for distinguishing the type of activity, e.g., respiration derived from microbial activity of nitrifiers or ammonia oxidizers. Nonetheless, an indicator of soil microbial communities is the **MBC/MBN ratio**, which typically has a value of 6 [3]. Lower values indicate bacterial dominance over fungi and vice versa.

Table 13. Soil microbial biomass carbon (MBC) and nitrogen (MBN) range of values measured in 176 arable soils [20]. *MBN values are estimated based on the ratio MBC/MBN = 6.

Interpretation	MBC (µg/g)	MBN* (µg/g)
Minimum	66.7	11.1
Mean	286.7	47.8
Maximum	846.0	141.0

KPI.EV.01.05 Soil water-holding capacity (WHC) and water content

The soil WHC determines the maximum amount of water that a soil can contain. This property is correlated to soil organic carbon content and soil texture (r^2=0.88) [21]. On the other hand, soil moisture or water content determines the availability of water in soil, which can change along with the seasons, and it is essential for both crops and microbial biomass. The mass difference between moist and dried soil is the measure of the water content, calculated on a gravimetric basis (g water /g soil or mL/g) as in the standard method ISO-11465 [22]. The **optimum water content for microbial processes is in the range of 40–60% of the maximum WHC** [3]. The WHC is measured in the field by repeatedly adding excess water to an exact mass of soil, determining the mass of water retained by the soil (mL/g or %). An approximation of WHC can be predicted from soil texture (Table 14).

Table 14. WHC values related to soil texture [21] and optimum water content.

Soil texture	WHC (%)	Optimum water content (%)
Clay – Sandy clay loam	~ 70	28 - 42
Sandy clay loam – Sandy loam	~ 60	24 - 36
Sandy loam – Loamy fine sand	~ 50	20 - 30

Dry seasons might reduce the water content in the soil, increasing the **irrigation efforts**. Similarly, wind turbines increase evapotranspiration, reducing soil moisture up to 20 km away from a wind farm [23]. This can mean an increment of irrigation efforts in surrounding crops. Conversely, integration of solar panels in crops produces shadows that reduce the air and soil temperatures, which allows for keeping soil moisture, reducing irrigation efforts. Therefore, integration of RES in crops has an important impact on **water management**, tracking of the soil water content is essential in agriculture and necessary to reduce wasting water.

3.2.2 *Biodiversity and pollution*

Finally, the following KPIs assess measurements of biodiversity and a range of pollutants, to monitor and reduce potential impacts in the environment and on the farm. These impacts can be due to changes in agricultural practices, integration of technologies such as solar panels or application of digestate for agricultural purposes, among other operations (Table 15).

Table 15. KPIs selected to determine biodiversity and pollution

KPI code	KPI name	Unit
KPI.EV.02.01	Vegetation diversity and cover	%
KPI.EV.02.02	Weed-insect pollinator indicator	Counts/h
KPI.EV.02.03	Soil emissions	g or µg per $m^2 \cdot h^1$
KPI.EV.02.04	Heavy metal pollution	CF (unitless)
KPI.EV.02.05	Pathogen contamination	CFU/g
KPI.EV.02.06	Microplastic contamination	%

KPI.EV.02.01 Vegetation diversity and cover

The agricultural intensification leads to loss of biodiversity, specially of plants and pollinators, hence its monitoring is essential to evaluate environmental impact of agricultural practices and integration of RES technologies. In ecology, higher diversity of plants means higher diversity of herbivores and predators, hence **higher biodiversity**. Some studies showed that diversified crops have a more complex food chain than monocultures, which leads to **a reduction of phytophagous pests and pesticides** [24]. Reducing pesticides increases vegetation cover, which also **reduces soil erosion risks** [25]. Thus, higher biodiversity in crop systems means several environmental and agricultural benefits. A good indicator of biodiversity in crop systems is the vegetation diversity and cover. To determine the impact of different management practices on crop systems, a **similarity index (SI)** can be calculated as the percentage of the difference in vegetation diversity [3]:

Equation 5. Similarity index of diversity , to compare between treatments.

$$SI = 100 * 2C/(A + B)$$

Where A and B are the number of species/plants found in plots A (treatment 1) or B (treatment 2) at a time, preferably in spring, and C is the number of common species/plants in both plots A and B. This similarity index can also be applied to compare a crop and a wild area to calculate the percentage of biodiversity loss. Ideally the SI should tend to 100%, meaning that protected area and cropping area have similar plant cover and diversity. Though this case is highly improbable, the aim of this KPI is to track the ecosystem status to prevent its degradation.

KPI.EV.02.02 Weed-insect pollinator indicator

Besides plants, pollinators are great bioindicators to evaluate the impact of agriculture on biodiversity, due to the reduction on nectariferous plants. However, monitoring pollinator diversity is laborious. Pollinator populations vary heavily depending on the season, climatic zone, weather, high, and vegetation [26], [27]. Therefore, to evaluate the degradation level (based on pollinators) of a region, reference values need to be measured in the same region to be compared, this requires representative study areas (well-conserved and big enough areas) and identification of all species. Getting these requirements in agricultural areas might be difficult, due to the degradation level of the surrounding environment, especially for pollinators. A study [28] suggests an alternative that might be better adapted to the agricultural environment, it is to focus on few species of pollinators related to specific weeds. Weeds are particularly affected by agriculture due to herbicides and insecticides, however they play an important role in ecosystem [28]. Despite weeds can be self-pollinated, pollination through insects and wind is necessary to maintain genetic diversity. Besides, weeds are a persistent food source for insect pollinators, creating weed-insect pollinator mutualistic interactions that serves as a local indicator of biodiversity [28].

To **monitor weed-insect pollinator interactions** in agricultural lands, few rare autochthonous weed-insect pollinator networks need to be selected. The mentioned study [28] suggests few **key networks** found in temperate climates in Europe: 1) the *Geometridae* (e.g., *E. biangulata*) and *Bombyliidae* species visiting *Caryophyllaceae*, 2) the *Papilionidae* (e.g., *P. machaon*) foraging on *Apiaceae*, and 3) the *Syrphidae* (e.g., *E. arbustorum*) visiting rare *Asteraceae* (e.g., *G. segetum*). **Counting the visits of these specific insects to specific weeds in a period, preferable in spring,** allows us to track key pollinators in small areas, such as margins of agricultural lands. Comparisons between cropping areas and wild areas can be done applying the similarity index as for 'KPI.EV.02.01 Vegetation diversity and cover', where A and B would be the number of visits of specific weed-insect pairs occurring in plots A (cropping area) and B (wild area) at a time, preferably in spring, and C is the number of visits from common species in both plots A and B. In the case of a non-degraded habitat, the count of weed-pollinators in protected areas and cropping areas should be the same (SI=100%). However, this case is again highly improbable, then, the aim of this KPI is to track the ecosystem status to prevent its degradation. In conclusion, tracking weed-insect pollinator interactions is a methodical strategy to evaluate in a simplified way the impact on pollinator diversity.

KPI.EV.02.03 Soil emissions

The soil has the potential to be both **sink and source of greenhouse gases (GHG)**. Greenhouse gases, most importantly CO_2, CH_4 and N_2O, can be released from soil, especially after wet-to-dry transitions in the soil, or due to the application of mineral fertilizers, livestock manure, or management practices such as tillage, among others [29]. Considering this, **soil emissions are responsible of almost half of the emissions from the agricultural sector** [1], [29]. Therefore, monitoring soil emissions is a good practice to ensure that soil is serving more as a sink than as a source of GHG, applying mitigation measures when needed and reducing the environmental impact of farms.

Standardization efforts are being made to measure soil emissions, up today different methods were tested and compared offering **high uncertainty** [30]. This is mostly because results interpretation depends heavily on meteorological conditions and soil characteristics, besides agricultural practices. Therefore, no standard thresholds can be provided, further research is needed. Instead, here is presented an example of monitoring soil emissions in crops over a year, measuring amount of each gas per unit of surface and time (Figure 5).

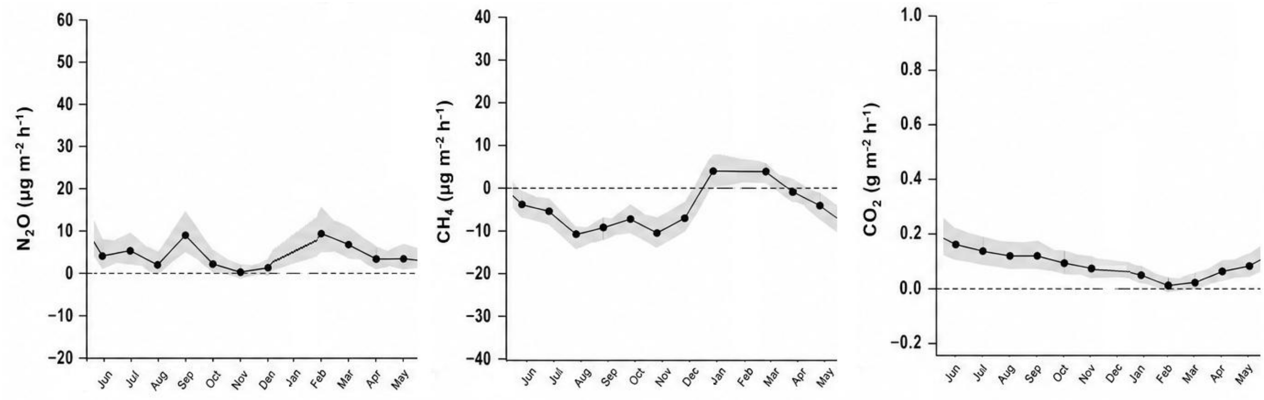

Figure 5. Example of seasonal GHG soil emissions, from crops in a fine loam over clay soil, located in an Atlantic-central pedoclimatic zone. The image was extracted from [31], modified with AI and human reviewed. Modifications consisted of averaging measurements from different crops (bioenergy crops and annual arable crops) of a selected year, and addition of interval confidence.

KPI.EV.02.04 Heavy metal pollution

Anaerobic digestion (AD) is a technology that treat organic waste streams and produce biogas and digestate, which is primarily used as fertilizer, and it can contain a high proportion of heavy metals due to concentration processes. Many heavy metals are necessary for plant growth, such as cadmium, copper, nickel or zinc, whereas others are toxic, such as chromium, lead, mercury or arsenic. Legal fertilizers comply with regulations that control the heavy metal composition, although **heavy metals can be accumulated in soil**, hence their application should be controlled over time.

Control of the addition of heavy metals to agricultural lands is required, but monitoring the content of heavy metals in soil is often disregarded. It is essential to identify the soil baseline and the soil needs to avoid excessive application and accumulation, which can lead to crop diseases, soil contamination and groundwater pollution.

There are a few standard methods to measure heavy metals in soil, the most extended is the ISO-11466 [32], but there is no international consensus on limits of heavy metal content in soil. Limits can vary between regions, this is because it heavily depends on the type of soil, pH, weather and crops; hence, most of the regulatory limitations are applied to fertilizers rather than soils. Limitations on the addition of heavy metals over time should also be considered, for instance, the Spanish Government has general limits for the addition of heavy metals to soil per year [33] (Table 16). Herein is proposed a list of values of heavy metal content in a soil that is generally considered not contaminated, these values are averaged from multiple references all over the world [34], [35], [36], [37], [38], [39], [40]:

Table 16. Average content of heavy metals in a non-contaminated soil and addition limits per year [33]. ND means 'not determined'.

Heavy metal	Baseline soil (mg/kg)	Limits of addition (g/ha/year)
Arsenic (As)	6	ND
Mercury (Hg)	0.06	150
Cadmium (Cd)	0.12	150
Chrome (Cr)	70	ND
Copper (Cu)	30	2400
Lead (Pb)	60	1500
Nickel (Ni)	40	600
Zinc (Zn)	65	6000

The **contamination factor (CF)** is a methodology widely used to evaluate the level of soil pollution due to individual heavy metals [38]. The **pollutant load index (PLI)**, based on CF, is to evaluate the level of soil pollution due to a combination of heavy metals:

Equation 6. Contamination factor (CF) for individual metals.

$$CF = C_S / C_{Ref}$$

Equation 7. Pollutant load index (PLI) for combination of metals.

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times \ldots \times CF_n}$$

Where C_S is the content of a determined heavy metal in soil (mg/kg) and C_{Ref} is the reference value of a determined heavy metal content in soil (mg/kg), this can be the baseline soil. The interpreted classes for CF are: CF < 1, indicates pristine environment; 1 ≤ CF < 3, indicates moderate contamination; 3 ≤ CF < 6, indicates high contamination; and CF ≥ 6, denotes very high contamination. The interpreted classes for PLI are: PLI > 2 denotes significant deterioration and 0 < PLI < 1 denotes baseline level pollution [38].

KPI.EV.02.05 Pathogen contamination

Digestate from AD is primarily used as fertilizer and **its composition in pathogens is notably lower** in comparison to the raw organic waste. Different AD operations coupled with pre- and post-treatments drives pathogen reduction, being **temperature the most relevant parameter** to this aim [41]. Nonetheless, the **hygienization capacity of AD can be insufficient** and microbial analysis must be done to evaluate the biosafety level of digestate prior land spreading.

European regulations established standard methods to monitor human-harmful bacteria, these methods are based on traditional bacteria quantification (CFU, colony forming units): isolated bacteria grown in specific media. According to Annex V of Regulation (EU) No 142/2011 (which implements Regulation (EC) No 1069/2009), compost and digestate products must meet two microbiological standards:

- for *E. coli* or *Enterococcaceae* (n = 5, c = 1, m = 1000, M = 5000), for *Salmonella sp.*, it must be absent in 25 g samples (n = 5, c = 0, m = 0, M = 0).

Where, n refers to the number of samples tested; m (CFU/g soil) is the acceptable threshold below which all results are satisfactory; M (CFU/g soil) represents the level above which results are considered unacceptable; and c indicates how many samples may fall between m and M while still meeting compliance, provided the remaining samples are at or below m. Monitoring requirements specify that *E. coli* or *Enterococcaceae* should be measured during or immediately after treatment to assess process performance, whereas *Salmonella* must be tested using composite samples collected during the storage phase of the digestate or compost [42].

European regulations demand limits for human and animal safety; however, pathogens can also affect the soil microbiome and plants. Control of plant and soil pathogens requires the use of antibiotics, which can lead to antibiotic-resistances [43], [44]. Therefore, human, animal, plant and environmental safety are interconnected, and a holistic approach should be taken. This means to monitor all-kingdom pathogens in agricultural amendments and to promote soil microbial diversity, which has been proven to be a key suppressor of pathogens [45]. However, monitoring all-kingdom pathogens through traditional methods is laborious. On the other hand, time-effective and accurate microbial analysis, such as DNA sequencing and qPCR, is expensive. Further **research is needed to identify acceptable pathogen thresholds** in amendments and to standardize methods for their monitoring and regulation.

KPI.EV.02.06 Microplastic contamination

Conversely to pathogen content, **solid digestates can have slightly more microplastics (<5 mm particles) than raw organic waste**, being between 41 and 3,298 particles/kg (wet weight) in raw digestate, 319 to 3604 particles/kg in solid digestate, and 7 to 38 particles/kg in liquid digestate [46]. Microplastics originate from all kinds of sources and processes. In addition, microplastic biodegradation is a slow process (a matter of at least decades), and **they are accumulating in soil**. Low concentrations of microplastics in soil (2%) already reduce bacterial diversity by over 20%. Microplastics also transport emergent contaminants such as polycyclic aromatic hydrocarbons, bisphenol A and phthalates, increase a 30% the earthworm mortality, reducing crop yields by over 20%, and ending up in the food chain with important health risks [47].

The best approach to reduce microplastic contamination is to reduce the source; hence, it is essential to reduce the use of plastics to the bare minimum. In fact, the agricultural sector is the second most important source of intentional microplastic release (24%), coming from polymers added to provide properties to fertilizers. For this reason, the European Regulation (EU) 2023/2055, amends Annex XVII of the REACH Regulation and **restricts microplastics intentionally added to fertilizers to ≤0.01% by weight** of the product, which can be measured through the **standard method ISO 24187** [48]. In 2026, a biodegradability criterion will enter into force within this regulation. However, more efforts must be made to eradicate microplastic release and contamination. Organic fertilizers rather than mineral fertilizers (that can contain plastic additives) should be promoted, besides further technological development to treat contaminated soils.

4. CONCLUSIONS

This deliverable presents a practical and flexible framework of agricultural and environmental Key Performance Indicators to assess the integration of renewable energy sources within agro-communities. The proposed indicators support the evaluation of crop productivity, soil quality, nutrient management, biodiversity, greenhouse gas emissions, and pollution risks associated with RES deployment in farming systems.

By combining agronomic and environmental perspectives, the KPI framework contributes to both sustainability and resilience assessment. Indicators such as nutrient use efficiency, soil organic matter, biodiversity, and farm GHG emissions help evaluate resource efficiency, environmental protection, and climate mitigation performance. At the same time, indicators related to soil health, microbial activity, water-holding capacity, and crop performance provide relevant information on the capacity of farming systems to adapt to environmental stress and changing climatic conditions.

The framework also supports informed decision-making by helping stakeholders identify synergies, trade-offs, and potential negative impacts linked to RES integration. Standardized methodologies and interpretation criteria improve consistency and comparability across different farming systems while maintaining flexibility to adapt to local conditions and management practices.

However, several limitations and data gaps remain. Agricultural systems are highly variable, and KPI interpretation can be influenced by climatic conditions, soil heterogeneity, crop type, and management practices. Some indicators rely on generalized threshold values that may not fully represent local conditions, while others, such as microbial activity, pathogen contamination, and microplastic pollution, still face methodological and regulatory uncertainties. In addition, some environmental interactions and long-term impacts cannot be fully captured through a limited set of indicators.

Overall, the proposed KPI framework provides a solid basis for monitoring the sustainability and resilience of RES-integrated agro-communities. It supports the transition towards more resource-efficient, climate-resilient, and environmentally sustainable farming systems, while remaining adaptable for future refinement as additional scientific knowledge and monitoring data become available.

5. REFERENCES

[1] FAO, "Greenhouse gas emissions from agrifood systems Global, regional and country trends, 2001-2023," 2025. https://doi.org/10.4060/cd7300en

[2] J. Deng *et al.*, "Insights into plant size-density relationships from models and agricultural crops," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 109, no. 22, pp. 8600–8605, May 2012, https://doi.org/10.1073/pnas.1205663109

[3] J. Álvaro-Fuentes, D. Lóczy, S. Thiele-Bruhn, and R. Zornoza, *HANDBOOK OF PLANT AND SOIL ANALYSIS FOR AGRICULTURAL SYSTEMS Crop diversification and low-input farming across Europe: from practitioners' engagement and ecosystems services to increased revenues and value chain organisation*. 2019.

[4] P. Dąbrowski, B. Pawluśkiewicz, H. M. Kalaji, and A. H. Baczewska, "The effect of light availability on leaf area index, biomass production and plant species composition of park grasslands in Warsaw," *Plant Soil Environ.*, vol. 59, no. 12, pp. 543–548, Dec. 2013, https://doi.org/10.17221/140/2013-PSE

[5] P. Villar Mir and J. M. Villar Mir, *Guia de la fertilitat dels sòls i la nutriciò vegetal en producció integrada*. 2016.

[6] S. R. Oliveira, J. A. Gomes Neto, J. A. Nóbrega, and B. T. Jones, "Determination of macro- and micronutrients in plant leaves by high-resolution continuum source flame atomic absorption spectrometry combining instrumental and sample preparation strategies," *Spectrochim. Acta Part B At. Spectrosc.*, vol. 65, no. 4, pp. 316–320, Apr. 2010, https://doi.org/10.1016/j.sab.2010.02.003

[7] Pere Villar Mir and Miquel Arán Mayoral, *Guia d'interpretació d'anàlisis de sòls i plantes*. 2008.

[8] K. A. Congreves, O. Otchere, D. Ferland, S. Farzadfar, S. Williams, and M. M. Arcand, "Nitrogen Use Efficiency Definitions of Today and Tomorrow," *Front. Plant Sci.*, vol. 12, Jun. 2021, https://doi.org/10.3389/fpls.2021.637108

[9] M. Andrades and M. E. Martínez, "Fertilidad Del Suelo Y Parametros Que La Definen," in *Material Didáctico. Agricultura y Alimentación, 3*, 4th ed., Universidad de La Rioja, 2022.

[10] ISO-14235, "Soil quality: Determination of organic carbon by sulfochromic oxidation," 1998, *ISO (International Organization for Standardization)*.

[11] APHA-2540. Standard Methods Committee of the American Public Health Association, American Water Works Association, and Water Environment Federation. 2540 solids In: Standard Methods For the Examination of Water and Wastewater. Lipps WC, Baxter TE, Braun-Howland E, editors. Washington DC: APHA Press.

[12] ISO-11263, "Soil quality: Determination of phosphorus- Spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution," 1994, *ISO (International Organization for Standardization)*.

[13] A. Bogdan, A. A. R. Aguilar, O. Nys, E. Michels, and E. Meers, "Phosphorus Availability in Recycled Fertilizers: Comparison of 11 Chemical Extraction Methods with Plant Uptake During a 7-Month Growth Experiment," *J. Soil Sci. Plant Nutr.*, vol. 23, no. 1, pp. 693–705, Mar. 2023, https://doi.org/10.1007/s42729-022-01075-5

[14] R. G. McClaren and K. C. Cameron, "Soil Science – an introduction to the properties and management of New Zealand soil," Auckland: Oxford University Press, 1990, pp. 228–232.

[15] ISO-11265, "Environmental solid matrices — Determination of the specific electrical conductivity," 2025, *ISO (International Organization for Standardization)*.

[16] A. Winding, K. Hund-Rinke, and M. Rutgers, "The use of microorganisms in ecological soil classification and assessment concepts," *Ecotoxicol. Environ. Saf.*, vol. 62, no. 2 SPEC. ISS., pp. 230–248, 2005, https://doi.org/10.1016/j.ecoenv.2005.03.026

[17] ISO-14240, "Soil quality: Determination of Soil Microbial Biomass," 1997, *ISO (International Organization for Standardization)*.

[18] M. R. Carter *et al.*, "Interpretation of microbial biomass measurements for soil quality assessment in humid temperate regions," *Can. J. Soil Sci.*, 1999, https://doi.org/10.4141/S99-012

[19] W. J. Wang, R. C. Dalal, P. W. Moody, and C. J. Smith, "Relationships of soil respiration to microbial biomass, substrate availability and clay content," 2003. [Online]. Available: www.elsevier.com/locate/soilbio

[20] M. Vohland, M. Harbich, M. Ludwig, C. Emmerling, and S. Thiele-Bruhn, "Quantification of Soil Variables in a Heterogeneous Soil Region With VIS–NIR–SWIR Data Using Different Statistical Sampling and Modeling Strategies," *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, vol. 9, no. 9, pp. 4011–4021, Sep. 2016, https://doi.org/10.1109/JSTARS.2016.2572879

[21] R. Bordoloi, B. Das, G. Yam, P. K. Pandey, and O. P. Tripathi, "Modeling of Water Holding Capacity Using Readily Available Soil Characteristics," *Agricultural Research*, vol. 8, no. 3, pp. 347–355, Sep. 2019, https://doi.org/10.1007/s40003-018-0376-9

[22] ISO-11465, "Sludge and solid environmental matrices- Determination of dry residue or water content and calculation of the dry matter fraction on a mass basis," 2025, *ISO (International Organization for Standardization)*.

[23] Z. Liu, G. Li, and G. Wang, "Can wind farms change the phenology of grassland in China?," *Science of the Total Environment*, vol. 832, Aug. 2022, https://doi.org/10.1016/j.scitotenv.2022.155077

[24] S. Hatt, T. Lopes, F. Boeraeve, J. Chen, and F. Francis, "Pest regulation and support of natural enemies in agriculture: Experimental evidence of within field wildflower strips," *Ecol. Eng.*, vol. 98, pp. 240–245, Jan. 2017, https://doi.org/10.1016/j.ecoleng.2016.10.080

[25] G. M. Gurr, S. D. Wratten, W. E. Snyder, and D. M. Y. Read, *Biodiversity and Insect Pests: key issues for sustainable management*. John Wiley & Sons, 2012. https://doi.org/10.1002/9781118231838

[26] J. Fourrier *et al.*, "Is it safe for honey bee colonies to locate apiaries near wind turbines?," *Entomologia Generalis*, vol. 43, no. 4, pp. 799–809, 2023, https://doi.org/10.1127/entomologia/2023/1858

[27] M. Graham *et al.*, "Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem," *Sci. Rep.*, vol. 11, no. 1, 2021, https://doi.org/10.1038/s41598-021-86756-4

[28] O. Rollin *et al.*, "Weed-insect pollinator networks as bio-indicators of ecological sustainability in agriculture. A review," Mar. 01, 2016, *Springer-Verlag France*. https://doi.org/10.1007/s13593-015-0342-x

[29] G. Chataut, B. Bhatta, D. Joshi, K. Subedi, and K. Kafle, "Greenhouse gases emission from agricultural soil: A review," Mar. 01, 2023, *Elsevier B.V.* https://doi.org/10.1016/j.jafr.2023.100533

[30] ISO-20951, "Soil Quality: Guidance on methods for measuring greenhouse gases and ammonia fluxes between soils and the atmosphere," 2019, *ISO (International Organization for Standardization)*. [Online]. Available: https://standards.iteh.ai/catalog/standards/iso/cb295624-5e9a-40f7-bfaa-b5a016465ce8/iso-20951-2019Website:www.iso.orghttps://standards.iteh.ai/catalog/standards/iso/cb295624-5e9a-40f7-bfaa-b5a016465ce8/iso-20951-2019

[31] J. Drewer, J. W. Finch, C. R. Lloyd, E. M. Baggs, and U. Skiba, "How do soil emissions of N2O, CH4 and CO2 from perennial bioenergy crops differ from arable annual crops?," *GCB Bioenergy*, vol. 4, no. 4, pp. 408–419, 2012, https://doi.org/10.1111/j.1757-1707.2011.01136.x

[32] ISO-11466, "Soil Quality: Extraction of Trace Elements Soluble in Aqua Regia," 1995, *ISO (International Organization for Standardization)*.

[33] BOE, *Real Decreto 1051/2022, de 27 de diciembre, por el que se establecen normas para la nutrición sostenible en los suelos agrarios*. Spain, 2022.

[34] J. Jarva, "Geochemical baselines in the assessment of soil contamination in Finland," 2016.

[35] K. Hans Wedepohl, "The composition of the continental crust," *Geochim. Cosmochim. Acta*, vol. 59, no. 7, pp. 1217–1232, Apr. 1995, https://doi.org/10.1016/0016-7037(95)00038-2

[36] Z. Hu and S. Gao, "Upper crustal abundances of trace elements: A revision and update," *Chem. Geol.*, vol. 253, no. 3–4, pp. 205–221, Aug. 2008, https://doi.org/10.1016/j.chemgeo.2008.05.010

[37] C. Reimann and P. de Caritat, "Establishing geochemical background variation and threshold values for 59 elements in Australian surface soil," *Science of the Total Environment*, vol. 578, pp. 633–648, Feb. 2017, https://doi.org/10.1016/j.scitotenv.2016.11.010

[38] S. C. Nde, O. M. Felicite, G. S. Aruwajoye, and L. G. Palamuleni, "A meta-analysis and experimental survey of heavy metals pollution in agricultural soils," *Journal of Trace Elements and Minerals*, vol. 9, Sep. 2024, https://doi.org/10.1016/j.jtemin.2024.100180

[39] P. De Caritat *et al.*, "Comparing results from two continental geochemical surveys to world soil composition and deriving Predicted Empirical Global Soil (PEGS2) reference values," *Earth Planet. Sci. Lett.*, vol. 319–320, pp. 269–276, Feb. 2012, https://doi.org/10.1016/j.epsl.2011.12.033

[40] M. Fleischer, "Recent estimates of the abundances of the elements in the earth's crust," 1953. Accessed: May 05, 2026. [Online]. Available: https://doi.org/10.3133/cir285

[41] L. Álvarez-Fraga *et al.*, "A meta-analysis of pathogen reduction data in anaerobic digestion," Jan. 01, 2025, *Elsevier Ltd*. https://doi.org/10.1016/j.rser.2024.114982

[42] P. Piveteau, C. Druilhe, and L. Aissani, "What on earth? The impact of digestates and composts from farm effluent management on fluxes of foodborne pathogens in agricultural lands," *Science of The Total Environment*, vol. 840, p. 156693, Sep. 2022, https://doi.org/10.1016/j.scitotenv.2022.156693

[43] Q. L. Chen, H. L. Cui, J. Q. Su, J. Penuelas, and Y. G. Zhu, "Antibiotic Resistomes in Plant Microbiomes," Jun. 01, 2019, *Elsevier Ltd*. https://doi.org/10.1016/j.tplants.2019.02.010

[44] Y. Yu *et al.*, “Plants select antibiotic resistome in rhizosphere in early stage,” *Science of the Total Environment*, vol. 858, Feb. 2023, https://doi.org/10.1016/j.scitotenv.2022.159847

[45] B. K. Singh *et al.*, “Plant pathogens, microbiomes, and soil health,” Aug. 01, 2025, *Elsevier Ltd.* https://doi.org/10.1016/j.tim.2025.03.013

[46] Z. Yang *et al.*, “Occurrence of macroplastics and microplastics in biogenic waste digestate: Effects of depackaging at source and dewatering process,” *Waste Management*, vol. 154, pp. 252–259, Dec. 2022, https://doi.org/10.1016/j.wasman.2022.10.018

[47] M. Sobhi *et al.*, “Characteristics, limitations and global regulations in the use of biogas digestate as fertilizer: A comprehensive overview,” Dec. 20, 2024, *Elsevier B.V.* https://doi.org/10.1016/j.scitotenv.2024.177855

[48] ISO-24187, “Principles for the analysis of microplastics present in the environment,” 2023, *ISO (International Organization for Standardization)*.

HarvREStGreener Farming with RES

The project

The HarvREStproject aims to enhance the sustainable production of renewable energy at farm-level. This approach not only makes farms climate-neutral but also optimizes production, reduces their impact on natural resources and biodiversity, and provides energy services to communities, thereby diversifying economic income. However, deciding how best to integrate renewable energy sources (RES) on a farm is not without its challenges. The decision is a complex one, with many factors to consider. Due to this, HarvREStseeks to identify, understand, and overcome the existing barriers hindering the widespread adoption of this innovative approach. Current initiatives often overlook the complex interactions and factors within the farming and RES context, resulting in ineffective support for decision-making based on accurate projections, estimations, and forecasts. HarvREStwill therefore consolidate and enhance existing knowledge, creating an Agricultural Virtual Power Plant capable of running diverse scenarios and farm configurations. This tool will determine the best operational procedures for a given RES solution, providing valuable data to a decision support system. This system will weigh trade-offs and key indicators, offering tailor-made recommendations to farmers and policymakers.

PARTNER		SHORT NAME
circe Creating together	CIRCE Research Centre	CIRCE
Beta UVIC	BETA Technological Centre	UVic-UCC (BETA)
NORCE	NORCE	NORCE
TECNOALIMENTI	Tecnoalimenti	TCA
WHITE	WHITE	WR
Suite5 We Deliver Intelligence	Suite5 Data Intelligence Solutions Ltd.	Suite5
EnGreen	EnGreen	EnG
ConTerra	ConTerra	CT

Confagricoltura	Confagricoltura	CONFAGRI
Solidale del Circeo	Fattoria Solidale del Circeo	FSDC
Viñas del Vero Somontano	Viñas del Vero	VdV
Viñedos del Rio Tajo	Viñedos del Rio Tajo	VRT
sorigué	Sorigué	ACSA
GGE	Grønn Gårdsenergi AS	GGE
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