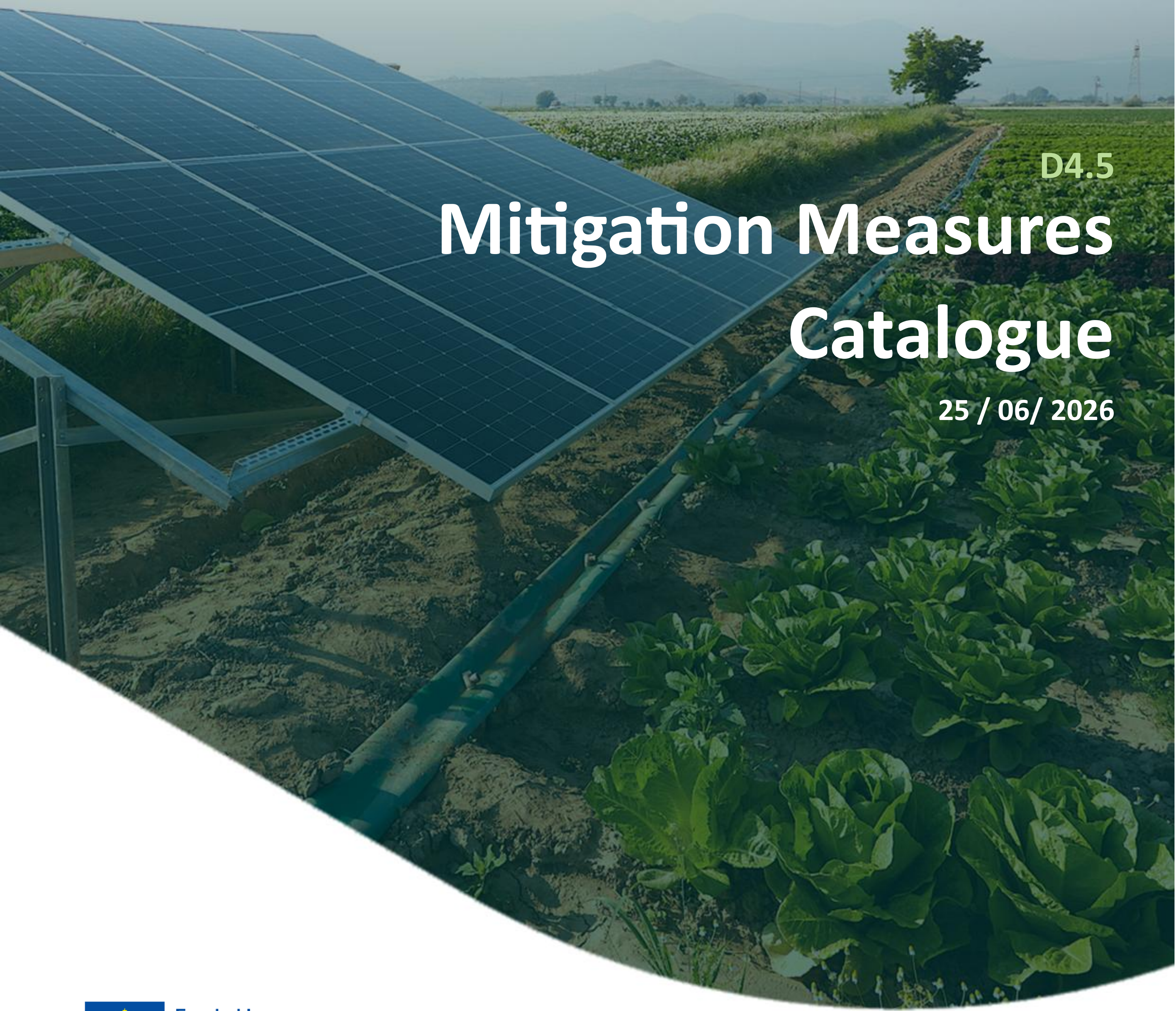
HarvRESt
Greener Farming with RES



D4.5

# Mitigation Measures Catalogue

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## PROJECT INFORMATION

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# ABBREVIATIONS

| | |
|---|---|
| AD | Anaerobic Digestion |
| AVS | Agrivoltaic systems |
| C | Carbon |
| $CH_4$ | Methane |
| $CO_2$ | Carbon Dioxide |
| COD | Chemical Oxygen Demand |
| $C_t$ | Total Soil Carbon |
| DM | Dry Matter |
| DSSCs | Dye-Sensitized Solar Cells |
| EMF | Electromagnetic Fields |
| EU | European Union |
| GHG | Greenhouse Gases |
| HTC | Hydrothermal Carbonisation |
| KPI | Key Project Indicator |
| LCA | Lyfe Cycle Assessment |
| MAOM | Mineral-Associated Organic Matter |
| N | Nitrogen |
| $NH_3$ | Ammonia |
| $NH_4^+$ | Ammonium ion |
| $NO_3^-$ | Nitrate |
| NFRV | Nitrogen Fertiliser Replacement Value |
| NVZs | Nitrate Vulnerable Zones |
| $N_t$ | Total Soil Nitrogen |
| OFMSW | Organic Fraction of Municipal Solid Waste |
| OPVs | Organic Photovoltaics |
| P | Phosphorus |
| PAR | Photosynthetically Active Radiation |
| PHAs | Polyhydroxyalkanoates |
| PHES | Pumped hydro-energy storage |
| POM | Particulate Organic Matter |
| PV | Photovoltaic |
| LER | Land Equivalent Ratios |

| | |
|---|---|
| RENURE | REcovered Nitrogen from manURE |
| RES | Renewable Energy Source |
| SOM | Soil Organic Matter |
| TKN | Total Kjeldahl Nitrogen |
| TOC | Total Organic Carbon |
| SOC | Soil Organic Carbon |
| VFAs | Volatile Fatty Acids |
| VPD | Vapour Pressure Deficit |
| WP | Work Package |

# EXECUTIVE SUMMARY

This deliverable provides a comprehensive assessment of the agronomic, environmental, biodiversity and social related impacts associated with three key renewable energy systems (RES) relevant to European agriculture—agrivoltaics (solar PV), anaerobic digestion for biogas production and other bioenergy systems, onshore wind energy and micro-hydropower. While these technologies offer substantial benefits for climate mitigation, farm resilience, and rural development, their deployment can also introduce system-specific trade-offs. The purpose of this report is to identify these impacts, synthesise the most up-to-date scientific and empirical knowledge, and propose a structured catalogue of mitigation measures that support sustainable co-production of food and energy.

Across all RES, the analysis highlights the dual opportunity and responsibility that renewable integration brings to agriculture. Agrivoltaics can enhance climate resilience, improve water-use efficiency, and maintain crop yields under stress conditions, but require careful design to avoid soil degradation, shading conflicts, and biodiversity loss. Biogas systems reduce methane emissions, valorise organic waste, and produce nutrient-rich digestate, yet they also risk nutrient imbalances, ammonia volatilisation, and eutrophication, especially in livestock-dense regions. Onshore wind power generates minimal agronomic disturbance and allows continued land use, but can affect local fauna, landscape perception, and soil structure during installation. Bioenergy obtained through thermochemical processes provide a stable supply of renewable energy, support biomass management for carbon sequestration and reduction of wildfire risks while revalorise agro-forest residues, but it can potentially produce habitat degradation, soil erosion and feedstock competition. Finally, hydropower is a key RES, but on-farm services are small scale systems with low power capacity, though, practically no negative impacts if farm dams are already available, otherwise its construction is highly unrecommended. These varied impacts underline the importance of context-specific planning, technology design, and stakeholder engagement.

The mitigation strategies presented in this deliverable combine technical, agronomic, environmental, and social approaches to minimise negative effects and maximise synergies. For agrivoltaics, key measures include optimising panel height, spacing, and orientation, maintaining permanent vegetation cover, managing rainfall redistribution, and incorporating biodiversity-friendly design. For biogas, effective mitigation relies on feedstock selection, digestate characterisation, advanced nutrient recovery technologies, low-emission spreading techniques, and strict compliance with nitrogen vulnerable zones restrictions and water-protection regulations. Wind energy mitigation emphasises careful site selection, micro-siting to minimise ecological disturbance, erosion control, and community engagement to address visual and noise concerns. Across technologies, cross-cutting recommendations include long-term monitoring, adaptive management, improved cooperation between farmers and energy developers, and coherent regulatory frameworks that reward sustainable practices.

This final version of the Mitigation Measures Catalogue establishes a robust foundation for the project's subsequent work on hybrid modelling, environmental assessment, and policy design.

# 1. INTRODUCTION

Agriculture plays a central role in food security, rural economies, and social cohesion, yet it is also highly dependent on energy-intensive inputs such as electricity, fossil fuels, and externally sourced fertilizers with significant environmental costs. In this context, **renewable energy sources (RES)** represent an important opportunity to reduce the energy and climate footprint of the agricultural sector while strengthening its sustainability, economic resilience and resource autonomy. Different RES, including solar power, bioenergy, and wind generation, are increasingly being deployed in rural areas to supply on-farm energy needs, create additional revenue streams, and support circular management of agricultural inputs and by-products.

RES operate at the intersection of energy systems, environmental processes, and socio-economic dynamics, **generating benefits that extend beyond energy provision** alone. By replacing fossil energy inputs and enhancing the efficiency of resource use, RES could create integrated effects that are reflected in multiple sustainability outcomes (Figure 1):

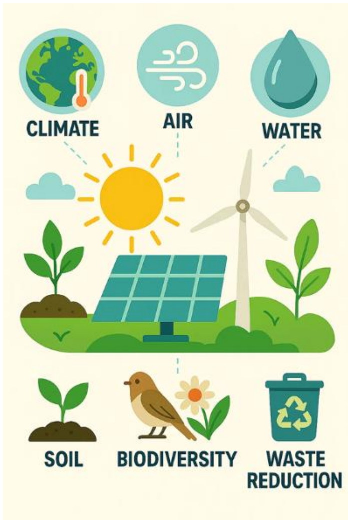


Figure 1. Environmental sustainability and renewable solutions (own source)

i) climate change mitigation through reduced dependence on carbon-intensive energy pathways

ii) lower greenhouse gas emissions that improve air quality and reduce atmospheric pollutants

iii) reduced pressure on critical resources such as water and biomass through more efficient energy conversion and agricultural practices

iv) improved soil health and fertility by promoting the recycling of organic matter and nutrients

v) enhanced biodiversity protection through lower pollutant loads and nature-inclusive land management, and vi) more efficient waste management by enabling circular economy practices that valorise organic residues and close material loops.

At the same time, the adoption of RES produces four interconnected but analytically distinct categories of impacts: **agronomic, environmental, biodiversity-related, and social**.

I. From an **agronomic perspective**, RES installations may influence soil properties and crop performance, with outcomes that range from yield reductions under shading constraints to productivity gains under heat or water stress, depending on crop type, management practices, and site characteristics. Similarly, the use of organic by-products from bioenergy processes can improve nutrient recycling and reduce reliance on mineral fertilisers but may require careful nutrient management to avoid local surpluses or losses.

II. In parallel, RES introduce **environmental impacts** associated with changes in land use, microclimatic conditions, and landscape identity, modifying local physical and chemical processes that regulate soil function and water dynamics.

III. Beyond these abiotic dimensions, RES also generate direct **biodiversity impacts** linked to alterations in ecological processes and habitat structure. The placement of energy infrastructure in agricultural areas can affect the distribution and abundance of organisms such as pollinators, soil fauna, and vegetation communities, with consequences for biogeochemical cycles and ecosystem functions. Biodiversity outcomes are highly context-dependent: research shows that nature-inclusive management practices can enhance vegetation diversity and ecological functions, whereas conventional configurations may create localised ecological pressures.

IV. Finally, **social perception of RES** in agricultural areas are also decisive for their development. Concerns about competition for farmland, changes in rural landscapes and cultural identity, and the distribution of economic benefits often shape attitudes toward RES projects in rural communities. Conversely, farmers who adopt RES frequently report gains in energy independence, reduced operating costs, and diversification of income sources through energy production and grid integration.

Overall, RES offer a strategic pathway to support the ecological transition of agriculture, but their full potential depends on balanced approaches that minimise trade-offs and maximise synergies between energy generation and agricultural production. **This deliverable** examines the main impacts of the RES most closely linked to agriculture, solar energy, biogas, onshore wind, bioenergy from thermochemical processes, and micro-hydro systems, while proposing measures to mitigate their environmental effects and identifying knowledge gaps to address in future research.

**The deliverable is structured** into a series of interconnected sections that progressively build a comprehensive understanding of the agronomic, environmental, biodiversity-related, and social impacts of integrating RES into agriculture. Following the introductory context, the document presents a detailed methodological framework describing the criteria for data collection, quality assessment, and the analytical dimensions applied throughout the study. The core chapters are organised by RES type, each addressed through a four-pillar assessment covering agronomic, environmental, biodiversity, and social impacts. For each technology, existing evidence is synthesised, and potential mitigation measures are identified. This is followed by a cross-technology analysis that consolidates mitigation strategies, highlights synergies among RES, and outlines monitoring and verification approaches relevant to long-term sustainability. The deliverable concludes with overarching recommendations, key findings for each RES, and implications for hybrid modelling in subsequent work packages, ensuring coherence with the broader objectives of the project.

# 2. METHODOLOGICAL FRAMEWORK

This deliverable presents a methodology that has been developed to comprehensively assess the agronomic, environmental and social impacts associated with the deployment of renewable energy in European agricultural systems. The approach combines recent scientific evidence and information from the initiatives mapped in Work Package 2 (WP2), agronomic results from Work Package 4 (WP4), and relevant technical documentation generated in earlier project stages. Integrating these sources enables diverse technologies to be analysed under a common framework, ensuring that the results reflect academic knowledge and real-world conditions.

## 2.1 RES relevant to agriculture

The first step in the assessment is to identify which renewable energy systems are relevant to the analysis. While the range of renewable energies is extensive, only a few interact directly with agriculture through land use, modification of the microclimate, alteration of soil parameters or connection to nutrient flows. For this reason, **the study focuses on ground-mounted solar photovoltaic energy, agrivoltaic systems, onshore wind energy, micro-hydro systems, biomass and anaerobic digestion for biogas production**. In the latter case, the analysis focuses specifically on digestate as this constitutes the point of interaction with agricultural systems. When applied as fertiliser or organic amendment, digestate can influence soil fertility, physical structure, nutrient cycles and emissions from agricultural activity. In addition to these core technologies, the deliverable will include a review on hybrid systems, that will be treated in less detail but will be included to provide a comprehensive overview of the relevant energy sources already identified in previous work.

## 2.2 Classification of existing data on agricultural impacts of selected RES

Once the targeted RES have been defined, the methodology organises the information into four analytical dimensions: **agronomic, environmental, biodiversity and social**. This allows for the integration and comparison of very diverse data. Agronomic sources include studies on plant physiology, soil dynamics, biogeochemical processes and crop yields. Environmental sources cover changes on microclimate, erosion, ecological connectivity and ecosystem services. Biodiversity sources cover changes in aerial and ground fauna and wild-plant diversity. Social sources include information on local perceptions, acceptance of infrastructure, compatibility with agricultural activities, land use and territorial governance. This framework is derived from the work carried out in WP2, which identified types of renewable integration and key impact mechanisms. It has been adapted to ensure its applicability to the technologies under consideration.

## 2.3 Criteria for data selection and quality assessment

The information gathering process has been guided by criteria of methodological soundness and relevance to European agricultural systems. Systematic searches of **scientific literature** were carried out using keywords related to the agronomic, environmental and social impacts of renewables in both conventional academic databases and open repositories of particular interest to European projects. These included Zenodo, Mendeley, ScienceDirect, Scopus, Google Scholar and sector-specific technical report platforms. These searches were complemented by a **review of institutional documents, energy agency reports, strategic environmental assessments and publications** from previous project initiatives and other relevant European experiences. Similarly, the results of WP3 and the practical initiatives of WP2 have been used to contrast and validate the patterns observed in the literature, providing further insight into the performance of technologies in real conditions.

## 2.4 Knowledge gaps and assumptions

This methodology recognises the existence of several knowledge gaps that restrict a thorough evaluation of the impacts. Hydropower systems on-farm, i.e. micro-hydro systems, are not very deployed, so there is little research on them; long-term studies on agrivoltaics in extensive European crops are still scarce; the information available on the indirect effects of wind power on agricultural soils is limited; and the composition of digestate varies considerably between contexts. Additionally, there is a lack of harmonised methodologies that enable the comparison of results between regions and production systems. To address these limitations, this deliverable makes explicit assumptions based on the literature, contrasts the identified patterns with the experimental data from WP3 and integrates observations from WP2's real-world initiatives, ensuring that the conclusions are supported by the best available evidence. This methodological basis enables us to proceed to the next chapter, which provides a detailed analysis of the current state of research into the agronomic, environmental and social impacts of the primary renewable technologies under consideration, along with the mitigation measures currently proposed in the literature and in real-world applications.

## 2.5 Mitigation measures definition for each RES and related KPIs

The final step of the methodology focuses on the definition of **mitigation measures for each renewable energy system** following the comprehensive assessment of agronomic, environmental, biodiversity, and social impacts associated with their deployment in agricultural systems. Mitigation measures are proposed in relation to specific negative impacts identified for the RES considered in this study with the objective of reducing adverse effects while preserving agronomic and energy performance. To support the operationalisation and comparability of these measures, **key performance indicators (KPIs)** identified in **Deliverable 2.2** of the HarvRESt project are integrated as recommended tools for **performance quantification**. The analysis highlights the presence of KPI gaps, particularly for environmental and biodiversity-related impacts such as habitat degradation, plant and animal biodiversity, and the presence of contaminants in soils and ecosystems. Then, these gaps were addressed in **KPIs developed on Deliverable 4.2,** which includes thresholds to **evaluate and monitor impacts**, strengthening the robustness of future impact assessments and supporting evidence-based mitigation strategies.

# 3. SOLAR ENERGY IMPACTS IN AGRICULTURE

Agrivoltaics is a multifunctional energy solution within agriculture, enabling simultaneous crop production and on-farm electricity generation. Adoption trends vary considerably, as farmers balance potential energy revenues with concerns about land-use compatibility and upfront investment requirements. Although agrivoltaic installations have demonstrated strong performance, often improving land-use efficiency and providing microclimatic benefits, they also introduce specific environmental and social considerations. These include potential shading effects on crop growth, changes in soil moisture dynamics, and visual or spatial constraints associated with panel structures. Nonetheless, these impacts are generally modest when compared with the impact of fossil fuels. This section evaluates the effects of integrating agrivoltaic systems into agricultural landscapes and highlights mitigation strategies that can support long-term, profitable, and sustainable co-production of food and energy.

## 3.1 Agronomic impact

Agrivoltaic systems (AVS) are known to engender a distinct microclimate in the area beneath and around the PV panels. These systems have been demonstrated to modify several environmental factors that are pivotal for plant growth, thereby exerting an influence on agricultural productivity and resource management [1], [2], [3].

### 3.1.1 *Shading effects*

The most direct impact of photovoltaic (PV) panels is the reduction and redistribution of incident solar radiation (Figure 2), specifically Photosynthetically Active Radiation (PAR), which is utilised by plants for photosynthesis. PAR levels beneath PV systems are notably lower than in open-sun conditions, exhibiting significant variability (e.g., 84.5–127 mmol $cm^{-2}$ $s^{-1}$ in shaded ground versus 243–1296 mmol $cm^{-2}$ $s^{-1}$ in open sun) [2]. One study reported a 30% reduction in PAR under PV panels [4], while another documented a peak reduction approaching 75% [5]. The extent of PAR attenuation is influenced by several design parameters, including panel density, system configuration (static vs. sun-tracked), module height, and transparency rate, which typically range from 13% to over 30% [6].


Figure 2. Effect of shade on the field of VRT

PV panels have also been observed to augment the fraction of diffuse radiation, which may be utilised more efficiently by plants, potentially offsetting minor decreases in direct radiation and enhancing leaf $CO_2$ uptake

[7]. However, concurrent shading has been shown to alter the spectral quality of light, with a concomitant increase in blue light (400–500 nm) and a decrease in red light (600–700 nm) [7]. Furthermore, it has been demonstrated that certain semi-transparent PV modules have the capacity to obstruct a proportion of the UV spectrum, with the potential to exert an influence on plant morphology [1]. Adaptive morphological responses to partial shading include an increase in total leaf area, changes in leaf orientation, and the development of greater plant height [2], [4], [8]. Such plasticity enhances the plant's ability to capture available light and partially compensates for the reduced irradiance beneath PV arrays [4]. However, shading may also lead to a modest delay in crop development or maturity, as observed in crops such as lettuce and winter wheat [2], [4]. In some cases, this delayed growth may result in a prolonged harvest window, which could provide economic or logistical advantages, particularly in market-sensitive crops [3]. The resultant shading patterns are non-uniform, exhibiting considerable spatial and temporal variability throughout diurnal and seasonal cycles due to solar altitude and panel arrangement [9]. This process gives rise to dynamic "microsites", distinguished by continuously evolving energy inputs [10].

### 3.1.2 *Altered air temperature*

Agrivoltaic systems have been shown to induce a measurable reduction in daytime air temperatures underneath the panels when compared to conventional open-field conditions [1]. The magnitude of these reductions can vary significantly, with studies reporting average reductions of approximately 1.2–1.3 [5], [11] and up to 4 °C in daily fluctuations. During extreme heat events, such as heatwaves, the magnitude can reach up to 5 °C for specific crops, such as grapes [12]. This localized cooling effect has been shown to be particularly beneficial in hot, arid regions, effectively alleviating heat stress for plants, farmworkers, and livestock [3].

Conversely, night-time temperatures can be marginally higher in agrivoltaic systems, e.g., 0.5 °C higher. While this may mitigate frost damage in temperate climates, it could also potentially enhance crop respiration rates, leading to a marginal reduction in net yield [6], [11]. The magnitude of temperature change is contingent upon ambient wind speed, ground surface conditions, and panel heights [9].

### 3.1.3 *Wind speed and direction*

Agrivoltaic systems have been noted to exert a notable influence on local wind regimes, and conversely, to be subject to the effects of ambient wind conditions. One of the primary impacts is the reduction in wind speed beneath the photovoltaic structures [2], [9]. This attenuation is largely due to the so-called "solar canopy," which increases surface drag and functions as an effective windbreak [13]. Empirical studies have consistently reported lower mean wind velocities in areas under solar panels when compared to adjacent control plots [13].

In addition to changes in speed, agrivoltaic systems have been noted to also induce alterations in wind direction, independent of the height of ground clearance structures [2], [9]. In certain configurations, a discernible shift in wind flow has been observed, with reorientation occurring perpendicular to the panel rows structures [9], [13]. Nevertheless, the consistency of this directional shift under conditions of high wind intensity remains uncertain and may vary according to local site characteristics [13].

### 3.1.4 *Altered soil temperature and moisture*

Soil temperature beneath PV systems tends to fall significantly compared to full sun exposure, especially during summer periods, when cooling effects of up to 7.7 °C have been recorded [2], [14], [15]. Conversely, during autumn and winter nights, the panels have been observed to paradoxically elevate soil temperatures

[15]. The moderation of soil temperatures has been demonstrated to be beneficial, promoting robust root growth and providing protection against abrupt temperature changes [15].

Furthermore, agrivoltaic systems have been shown to lead to consistent increases in soil moisture levels and enhanced retention capabilities. This phenomenon is primarily attributable to decreased soil evaporation rates resulting from the combined effects of shading and reduced wind speed [2], [5], [10], [16]. Consequently, agrivoltaic systems consistently exhibit lower Vapour Pressure Deficit (VPD), signifying higher atmospheric moisture content beneath the panels [2]. Documented reductions in VPD include 0.52 ± 0.15 kPa across a growing season in one study [11], and 0.50 ± 0.04 kPa in another [5]. Reducing VPD has been shown to be effective in preventing or alleviating the midday depression of photosynthesis, particularly in hot and arid environments. In such conditions, AVS have been shown to enhance cumulative $CO_2$ uptake: for example, by 33% in chiltepin pepper and 65% in cherry tomato when compared to conventional open-field cultivation [5], [11]. As well, irrigation water demand can be reduced by approximately 20%, with only a 10% reduction in yield or a modest extension of the harvesting cycle [2]. This trade-off may be deemed acceptable, particularly in contexts where water scarcity is a prevalent issue.

The enhanced performance of plants cultivated under AVS is attributed to their capacity to sustain elevated photosynthetic rates over extended periods throughout the day, a benefit that can be attributed to the buffered thermal and hydric conditions [5]. Furthermore, shade-tolerant species are particularly well-suited to these environments, as they tend to exhibit a steeper light response curve and a lower light compensation point, allowing for efficient carbon assimilation even under diminished irradiance [1].

### 3.1.5 *Rainfall redistribution*

AVS establish a unique microclimate beneath the panels that can significantly alter the hydrological dynamics of the land, leading to specific agronomic impacts related to water balance [2], [3], [17]. Solar panels act as an "umbrella," creating sheltered areas underneath that receive less rainfall, while concentrating collected fluxes along their edges [17]. This results in spatial heterogeneity of soil moisture, potentially leading to distinct moist patches under the panel edges and drier, sheltered areas directly beneath the panel [17]. Concentrated rainwater runoff discharged from the panel edges can exacerbate Hortonian overland flow (infiltration excess), thereby elevating the risk of soil erosion and gully formation, particularly on bare soil or during intense rainfall events [17], [18]. Thus, the development of rainwater harvesting and redistribution systems represents both a necessity and an opportunity to enhance the sustainability and resilience of agrivoltaic projects.

Rainwater harvesting systems can be integrated to collect water from PV modules, which can then be used for irrigation or for cleaning deposited dust on the modules [2], [17]. For optimal design, rainwater harvesting combined with electricity production can potentially lead to self-watering and self-powered farming [2].

### 3.1.6 *Climate resilience*

Agrivoltaic systems can play a pivotal role in enhancing crop resilience to climate change by providing protection against extreme weather events, including heat waves, drought, heavy rainfall, hail, and sunburn [11], [15], [19]. The moderated microclimate created under photovoltaic structures contributes to buffering crops from temperature extremes, potentially offsetting projected increases in ambient temperatures under future climate scenarios [5], [16].

This buffering effect is particularly critical in arid and semi-arid regions, where high solar radiation and limited water availability pose persistent threats to agricultural productivity [2], [3]. By mitigating environmental stressors, agrivoltaic systems support more stable yields and offer a promising strategy for climate-adaptive farming.

### 3.1.7 *PV infrastructure design*

The meticulous design of PV infrastructure is crucial for optimizing these dual-use systems, as it directly influences the microclimate beneath the panels and, consequently, mitigates impacts on crop growth, yield, and overall agricultural performance [1], [3], [20]. Careful, site-specific design is essential to ensure profitable operation and balance the trade-offs between energy production and crop yields [1], [21].

- **Panel height:** Panel height is a fundamental design variable in agrivoltaic systems, adjusting panel height serves as a key mitigation strategy for moderating temperature extremes, improving air circulation, and ensuring compatibility with diverse crop types and mechanization needs [1], [3], [20]. Higher panel elevations enhance vertical airflow and thermal dissipation beneath the array, contributing to localized cooling and reduced heat stress in crops, livestock, and farm labourers [1], [3]. For instance, panels installed at 4 m above vegetated ground have been shown to reduce air temperatures by up to 10 °C compared to configurations at 0.5 m over bare soil, underscoring the combined effects of elevation and surface cover on microclimatic outcomes [9]. Moreover, higher panel placement may indirectly improve PV efficiency by enhancing convective cooling of the modules themselves, particularly in hot climates [1].
- **Coverage ratio:** The distance between panel rows (inter-row spacing) and between individual panels (inter-panel spacing) which define the system's coverage ratio is a key determinant of light availability, crop performance, and localized microclimatic conditions within agrivoltaics systems [1], [2], [20]. Reduced panel density increases the proportion of photosynthetically active radiation (PAR) reaching the understory, with reported transmission rates ranging from 60% to 85% of open-field conditions under low coverage scenarios [2], [4]. In contrast, dense configurations (e.g., ≥50% coverage) have been shown to reduce PAR by over 40%, often leading to inhibited growth, especially in shade-intolerant crops [15], [20]. Coverage ratios of 25% or less are generally considered safe thresholds, below which crop performance remains largely unaffected [22].

  Beyond irradiance, panel spacing significantly modulates the AVS microclimate and hydrological function. Increased spacing enhances solar exposure and air circulation, moderates diurnal soil temperature fluctuations, and facilitates greater soil evaporation where appropriate [15], [23]. Conversely, denser arrays exert stronger microclimatic buffering, potentially benefiting crops in hot, arid climates by reducing evapotranspiration and mitigating heat stress [2], [5], [24]. Furthermore, strategic spacing improves the spatial distribution of rainfall by minimizing runoff concentration at panel edges, thereby enhancing soil moisture uniformity and reducing erosion risk [2], [17].
- **Orientation of PV panels:** The orientation of PV panels, defined by their tilt angle (relative to the horizontal) and azimuth angle (directional bearing), is a critical design parameter in AVS that influences not only solar energy capture but also the spatial and temporal distribution of light, microclimatic conditions, and rainfall interception [2], [3], [9]. While south-facing orientations (in the Northern Hemisphere) typically maximize annual energy yield, they also create pronounced light heterogeneity, with minimal irradiance directly beneath the modules and strong lateral gradients [2], [9]. Adjusting azimuth toward southeast or southwest can mitigate these effects, promoting more uniform sub-canopy lighting, which is particularly important for shade-sensitive crops [3]. Vertical east–west

bifacial systems further enhance light homogeneity and have been shown to reduce seasonal yield variability by minimizing extreme shading events [1], [2]. Tilt angle also directly impacts the angular distribution and quality of irradiance at the crop level. Steeper tilts increase the penetration of diffuse light into the system, which may enhance photosynthetic efficiency in certain crops [7], while flatter angles intensify direct shading. In systems prioritizing agricultural output, tilt adjustments may improve light diffusion even at the cost of minor reductions in energy yield [2], [3].

Hydrologically, panel orientation determines how rainfall is intercepted and redistributed. Shallow tilt angles and perpendicular orientations to prevailing winds often result in highly uneven runoff and concentrated flows along panel edges, increasing erosion risk and soil moisture heterogeneity [2], [4], [17]. Conversely, wind-aligned orientations or dynamic tilt adjustments can improve rainfall spread and infiltration uniformity, enhancing soil moisture availability and reducing localized degradation [2], [17]

- Tracking systems: particularly single-axis and dual-axis configurations, allow dynamic adjustment of PV panel orientation throughout the day or season, providing a powerful tool for optimizing both energy yield and agronomic performance in agrivoltaic systems [1], [3], [9], [20]. This dynamic light management has been shown to stabilize yields under variable climatic conditions, improve spatial uniformity of production, and increase land-use efficiency. For instance, tracked systems have produced higher Land Equivalent Ratios (LER) in crops such as lettuce and potatoes, and enabled yield preservation in grapevines exposed to heatwaves and drought [1], [12], [25]. Mobile tracking modules may also facilitate adaptive responses to wind direction, further improving rainfall distribution across the cultivated area [4], [17].

  However, tracking systems come with increased costs and design complexity. Anti-tracking periods, when panels are positioned to favour crop conditions rather than energy production, can slightly reduce total electricity output [9]. Despite this, the agronomic co-benefits may outweigh the marginal energy trade-offs in regions where climate resilience and water efficiency are priorities [1], [3], [20].

- Panel Material and Transparency: The choice of PV panel material, particularly regarding transparency and spectral properties, plays a key role in regulating light quality, microclimate, and overall crop compatibility in agrivoltaic systems [1], [3], [15], [23]. Semi-transparent PV panels allow partial transmission of solar radiation, enabling controlled shading while maintaining photosynthetically useful light beneath the panels [15], [23]. This is particularly beneficial for horticultural crops sensitive to thermal or light stress. In greenhouse and open-field settings, semi-transparent modules, especially crystalline silicon (c-Si) and thin-film types, have demonstrated strong agronomic compatibility. Lettuce yields, for example, were maintained under c-Si semi-transparent modules that reduced air temperatures by 1–3 °C, with no significant difference in fresh or dry weight compared to unshaded controls at shading rates up to 20% [1], [15]. Similar results have been reported for basil, tomatoes, and strawberries. Basil biomass was unaffected under tinted a-Si panels, while tomato growth remained comparable to unshaded areas under 47% transparent c-Si modules [1]. Berry crops such as strawberries, raspberries, and redcurrants have also shown promise under monocrystalline semi-transparent arrays in pilot trials [19]. Additionally, spectral-selective designs, such as Organic Photovoltaics (OPVs) or Dye-Sensitized Solar Cells (DSSCs), offer the potential to transmit crop-optimized wavelengths while converting unused bands to electricity, further aligning energy production with plant physiology [19].

- **Bifacial PV panels:** These panels present a compelling option in AVS due to their ability to capture both direct and reflected light, potentially increasing energy output by up to 20% compared to monofacial modules [1], [21]. When elevated or vertically mounted, these systems can enhance microclimate regulation, optimize light distribution, and reduce infrastructure impact [1], [20]. Yield outcomes under bifacial systems vary widely depending on crop type, system density, and climatic conditions. Positive or neutral impacts have been reported for several species. For instance, pasture grass yields rose by 13–39% depending on orientation [21] and strawberries and grasslands under moderate shading showed 15.6% and 3.7% yield increases, respectively [26]. However, yield reductions have been observed in more shade-sensitive crops or under high-density layouts. For example, soybeans, beans, garlic, and onions saw severe losses, up to 73%, highlighting the need for strict alignment of system design with crop light requirements [20].

## 3.2 Environmental impact

While the agrivoltaics dual-land-use approach aims to optimise the agricultural use and promote sustainable development, the potential impact on its environment must be considered in detail. This includes the risk of soil degradation through compaction, reduced organic carbon content, nutrient imbalance and erosion.

### 3.2.1 *Soil compaction*

Soil compaction represents a significant concern in agrivoltaic systems. The primary association pertains to the utilisation of heavy machinery during the construction phase of PV installations, a practice that has been observed to induce disruption to soil structure, diminish infiltration capacity, and compromise hydraulic properties [23], [27]. In a multi-site study, compaction levels were found to be 15.5% higher beneath solar panels compared to the adjacent pastures [27]. This phenomenon can result in a reduction of soil porosity. This decline in soil porosity has the potential to impede root penetration and hinder vegetation establishment, particularly in shaded areas where plant growth is already constrained. The resulting decline in root development and water cycling may further exacerbate compaction, reducing aeration and biological activity [27]. Disturbance to the soil is most intense during the construction phase; however, it may also occur periodically during maintenance or repair operations. This poses a long-term risk to soil health and biodiversity [14], [27].

However, the findings on compaction are not entirely consistent. In one study, no significant differences in compaction were observed relative to panel distance in grassland systems, and even less compaction was recorded near a tracker in a winter wheat field [28]. The findings indicate that compaction effects may diminish over time, possibly due to biological activity (e.g., earthworm activity) or site-specific factors such as reduced vehicular traffic or alternative construction methods [28].

The preservation of soil health in agrivoltaic systems is contingent upon the adoption of low-impact construction techniques. In the context of site preparation, the principle of minimal soil disturbance should be prioritised. This involves the avoidance of extensive grading and the limitation of the use of heavy machinery, particularly in areas that are sensitive or prone to erosion [23], [29]. In circumstances where this is possible, the existing vegetation should be preserved, and the natural topography should be integrated into the system design with a view to minimising soil disruption and ensuring the maintenance of hydrological function [29].

Additionally, the practice of managed grazing, particularly in the context of small livestock such as sheep, has been demonstrated to support vegetation control and organic matter cycling without the necessity for intensive machinery use. This approach offers ancillary benefits for soil health and farm diversification [14], [30], [31].

### 3.2.2 Altered soil organic fractions

The alteration of microclimate and the reduction of solar radiation beneath solar panels have been demonstrated to significantly influence soil organic carbon (SOC) dynamics. This environmental modification has been shown to result in diminished plant productivity and growth, which consequently leads to a reduction in plant-derived carbon inputs to the soil [27]. Consequently, changes in the chemistry of plant tissue and the quality of litter contribute to a decline in SOC content. Specifically, studies have reported a 9% reduction in SOC under solar panels compared to unshaded areas [27].

Particulate Organic Matter (POM), a highly labile and disturbance-susceptible fraction predominantly derived from plant material, is particularly vulnerable to these changes. Research has shown that there has been a decline in POM of 29.1% and 23.6% under solar panels in comparison to gaps and pastures, respectively [27]. A decline in POM has been demonstrated to exert a detrimental effect on critical soil properties, including aggregate stability, water infiltration, and erosion resistance [27]. Although mineral-associated organic matter (MAOM) is generally more recalcitrant, prolonged reductions in plant-derived carbon inputs could eventually lead to a decline in its levels [27]. Moreover, research conducted in natural grassland ecosystems has documented considerable declines in total soil organic matter (61%) and total nitrogen (50%) following seven years of operation of photovoltaic (PV) power plants. These diminished carbon inputs have the potential to impede microbial growth and disrupt the soil food web, consequently leading to reduced microbiological activity and nutrient cycling [15], [27], [28].

Composting is a mitigation practice that serves to enhance the quality of soil by introducing organic matter, thereby facilitating nutrient cycling. The integration of composted plant residues, food waste, and animal manure has been demonstrated to be a viable method of restoring fertility and reducing reliance on external inputs [30]. When combined with no-till or reduced tillage systems, composting contributes to the maintenance of soil structure and minimises disturbances that could compromise microbial activity or increase erosion risks. This is particularly relevant in fixed PV infrastructure settings [30].

### 3.2.3 *Nutrient imbalance and depletion*

The impact of AVS on soil nutrient dynamics is complex and often site-specific, depending on initial soil conditions, crop types, and management practices. In certain contexts, notably those involving degraded or barren land, the implementation of AVS installations has been demonstrated to result in a substantial enhancement of soil nutrient status [10], [30]. For instance, one study documented increases in soil nitrate-nitrogen ($NO_3$-N) concentrations ranging from 3.89 to 8.15 times, potassium levels from 3.48% to 29.97%, and available phosphorus [10]. In contrast, other studies, notably in temperate agricultural contexts or following multiple years of AVS operation, have documented declines in soil nutrient levels. For instance, a decline in total nitrogen levels of up to 50% and a decrease in the activity of key soil enzymes, such as phosphatase and sucrase, have been observed under PV panels [10], [15]. This evidence suggests that while AVS may enhance soil fertility in degraded environments, it can also induce nutrient imbalances or depletions in previously productive soils if plant-derived inputs decline over time [15].

### 3.2.4 *Erosion*

AVS have the capacity to both mitigate and intensify soil erosion, depending on the configuration of the system and the way the ground is managed. Photovoltaic panels offer a dual benefit in this regard, serving as both a physical barrier against direct rainfall and wind impact and aiding in the preservation of topsoil structure [21], [30]. The establishment or maintenance of native vegetation with deep root systems beneath panels has been demonstrated to further stabilise the soil and reduce runoff, thereby enhancing the protective effect of AVS installations [21].

On the other hand, the redistribution of rainfall caused by panel surfaces has been shown to increase the risk of Hortonian overland flow and subsequent erosion processes [17], [18]. It has been demonstrated that inadequate drainage, or an absence of vegetation capable of absorbing runoff, can result in severe soil erosion [32]. Precision irrigation systems, especially drip irrigation, further promote plant health by delivering water directly to the roots, thereby reducing surface wetting and the potential for nutrient leaching. This is of particular importance in preventing microbial disruption and compaction associated with over-irrigation or pooling in shaded areas [23]. Other mitigation measure can be biochar amendments, these can enhance the soil's sponge function by increasing water holding capacity, infiltration rates, and structural stability. Its utilisation has been associated with a 25–29% improvement in water retention and a comparable reduction in overland flow. Collectively, these factors contribute to lower erosion rates and improved microbial habitat conditions [15], [18].

## 3.3 Biodiversity

The effects of agrivoltaic systems on biodiversity are multifaceted, involving both risks and opportunities depending on infrastructure design, management practices, and the surrounding ecological context [33]. These systems can either disrupt or enhance biodiversity, with outcomes shaped by local conditions and implementation strategies.

### 3.3.1 *Direct effects from physical structures*

One of the primary concerns associated with agrivoltaic systems is the potential for habitat degradation and loss resulting from the installation and physical presence of PV infrastructure. Conventional solar developments often leave the ground beneath the panel's barren [2], and their construction typically involves extensive soil disturbance and vegetation removal, leading to the displacement of key organisms such as insect flower visitors [31]. These disruptions can fragment existing ecosystems and reduce the availability of critical resources for native species.

Additionally, solar panels may unintentionally act as ecological traps: the polarized light they emit can attract diurnal aquatic insects, while smooth, reflective surfaces may mislead birds and bats, sometimes resulting in collisions or inappropriate landing behaviours [31]. Supporting infrastructure such as fences and electrical grid components may further obstruct wildlife movement and alter animal behaviour [33].

### 3.3.2 *Indirect effects from altered microclimate*

Indirect effects linked to changes in microclimate and shading patterns also pose risks to biodiversity. Reduced sunlight under panels can alter plant community composition, particularly by suppressing heliophilic (sun-loving) species, which often fail to establish beneath panels and are limited to inter-row spaces [14]. These shifts can lead to a decrease in total plant biomass and flowering, especially under full shade conditions [14], [33]. In wetter or high-latitude environments, where heat and drought stress are less prevalent, shading may negatively affect most native plants, diminishing potential ecological benefits [14].

Pollinator populations are also affected, with studies showing reductions in pollinator abundance, richness, and diversity under heavily shaded panel rows [6], [31]. The reduced evaporation caused by shading can increase local humidity, creating favourable conditions for pathogens and parasites that affect crops [2]. Another debated concern involves the electromagnetic fields (EMFs) generated by solar infrastructure, which may interfere with nervous and immune function, circadian rhythms, fertility, and even pollination behaviour in some species, including honeybees and mammals [33]. However, these effects remain debated and require further research. Lastly, increased moisture and shade may favour invasive or opportunistic plant and fungal species, which can outcompete native flora and reduce both biodiversity and crop performance [33].

### 3.3.3 *Heterogeneous microbial activity*

The effects of AVS on soil microbial activity are variable and highly context dependent. Several studies have reported positive impacts, including increases in microbial biomass carbon, nitrogen, and phosphorus, as well as enhanced enzyme activities such as urease. These findings indicate improved soil fertility and nutrient cycling, particularly regarding phosphorus availability [10]. However, other studies have suggested negative effects. Shading has been demonstrated to exert an effect on the composition and diversity of soil microbial communities, with the potential to reduce the abundance of light-dependent bacterial and fungal taxa [15]. Furthermore, lower soil temperatures beneath the panels have been observed to suppress overall microbial metabolic activity, with some experiments recording a 50% decline in key enzymes involved in nutrient cycling [15], [28]. These findings highlight the importance of site-specific factors, including baseline soil conditions, management intensity, and climatic context, in influencing microbial responses to AVS [10].

### 3.3.4 *Positive and synergistic impacts*

Despite these concerns, agrivoltaic systems can also support biodiversity when designed and managed with ecological considerations in mind. By enabling the dual use of land for food and energy production, these systems reduce the need for additional land conversion, thereby helping to conserve natural habitats and reduce ecosystem fragmentation [2], [34]. Agrivoltaics can also actively contribute to habitat restoration. Properly managed systems can promote the growth of native vegetation and support pollinator populations by providing suitable flowering habitats [6], [21], [29], [33], [34]. Some U.S. states have introduced policies and incentive programs to promote pollinator-friendly solar farms (Figure 3), recognizing their potential role in restoring ecosystem services [34].

Figure 3. Beekeeping activity integrated into a photovoltaic installation, illustrating a dual land-use approach [129]

Finally, agrivoltaic systems can improve the welfare of animals and farm workers by creating cooler microclimates during heat waves and droughts [2], [29], [30]. Livestock sheltering beneath panels may benefit directly from the moderated temperatures, while their presence can support populations of dung-feeding insects, which in turn benefit species such as bats by maintaining food availability across trophic levels [31].

## 3.4 Social impact

The expansion of solar power is often limited by competition over land and by opposition from local communities. For agrivoltaics to advance, the technology must be embraced by the market, supported by community buy-in, and enabled by favourable local policies. Understanding the different facets of social acceptance, along with their associated challenges and advantages, becomes essential for guiding effective decisions that support agrivoltaic development.

### 3.4.1 *Market Acceptance*

Agrivoltaics emerges as a market-viable option that can relieve land-use tensions while maintaining competitive energy costs. A survey revealed that developers view agrivoltaics as technically feasible but often constrained by added complexity, safety considerations, and uncertain financial returns [35]. However, well-designed agrivoltaic systems, particularly those using tensile structures, achieve levelized costs of electricity comparable to ground-mounted PV, narrowing the perceived risk gap [36]. Agrivoltaics can add value through higher energy productivity, stable crop yields, and drought resilience, which can diversify revenue streams for farmers and improve project bankability. In addition, agrivoltaics not only reduces operational costs such as vegetation management but also enhances long-term market acceptance by providing a dual-benefit economic rationale [35], [36].

### 3.4.2 *Social perception and political perspectives*

Community support to solar development strengthens significantly when it is perceived as complementary, i.e., agrivoltaics, rather than competitive with agriculture. The rural resistance often stems from fears of farmland loss and shifts in landscape identity [35]. Agrivoltaics mitigates these concerns by preserving agricultural activity, allowing communities to maintain cultural and economic ties to farming. This perception is reinforced through empirical evidence showing that agrivoltaic systems can maintain 80–90% of land accessibility for conventional agriculture, reduce water stress, and even increase or stabilize yields under drought conditions [36]. These measurable benefits directly address local worries about food production and environmental pressures. Thus, agrivoltaics becomes not only a technological solution but a community-aligned land-use strategy that reinforces agricultural resilience while supporting clean energy adoption.

Agrivoltaic systems further demonstrated to outperform conventional energy systems across most environmental categories, offering lower GHG emissions, reduced eutrophication, better air-quality outcomes, negligible net land appropriation, and promoting rural employment, while contributing positively to 14 of the 17 UN Sustainable Development Goals [36]. These strong environmental and social credentials supply policymakers with evidence-based justification to promote agrivoltaics through supportive regulation, incentives, and integrated energy-agriculture planning [36].

# 4. BIOGAS PLANT IMPACTS IN AGRICULTURE

Biogas is a fuel that can be obtained from renewable sources containing organic matter, e.g., agricultural waste, farm waste, urban waste, etc. Biogas is produced through the anaerobic digestion (AD), this is a biological process in which biodegradable organic matter is partially degraded or broken down in the absence of oxygen by specific microorganisms, resulting in biogas and digestate [37]. Biogas is composed mainly of methane and carbon dioxide, which allows for its energy use. Digestate has a high-water content, as well as a significant amount of organic matter and nutrients [37]. Hence, its most common use is application to agricultural soils in order to increase crop yield and improve soil quality. For this reason, most of the impacts associated to the integration of AD into agriculture are related to digestate downstream treatments, especially spreading. This section reviews the different impacts of implementing AD in agriculture and mitigation strategies that can support a sustainable co-production of food and energy at long-term.

## 4.1 Agronomic impact

The impact of digestate in downstream treatments depends on its characteristics, which relates to the feedstock and the AD process. Therefore, to evaluate the full agronomic impact, insights on feedstock and AD process are also provided.

### 4.1.1 *Feedstock origin and on-farm synergies*

The composition of the feedstock entering an AD system is the primary determinant of digestate quality. Feedstocks differ widely in degradability, nutrient content, moisture, and contaminant load, leading to digestates with distinct chemical, physical, and biological properties [38]. Because digestate composition is essentially a “mirror” of the feedstock mixture, upstream feedstock management becomes a powerful lever not only for optimising biogas yields but also for shaping digestate quality, safety, and required downstream treatments. Therefore, depending on the feedstock origin, different digestate outputs can be expected:

- Lignocellulosic residues, such as cereal straw, maize stover, sorghum residues or bagasse, contain large proportions of cellulose, hemicellulose, and lignin [39]. Their structural recalcitrance slows hydrolysis and limits methane yield, often requiring longer retention times or pretreatment. Digestates originating from these materials therefore show high total solids and considerable fractions of undegraded lignin [38]. While beneficial for soil carbon sequestration, these residues can compromise soil incorporation at high application rates.
- Manure and slurries, by contrast, are rich in microbial biomass and nitrogen. During AD, a substantial share of organic nitrogen is mineralised into ammonium ($NH_4^+$), generating digestates with low C:N ratios and high $NH_4^+$/TKN (Total Kjeldahl Nitrogen) fractions [40]. These properties enhance short-term fertiliser value but make manure-based digestates highly vulnerable to ammonia volatilisation during storage and field application. Pig and poultry manures may generate inhibitory levels of free $NH_3$ unless adequately diluted [41], and heavy metals, pharmaceuticals, and antibiotics present in the original manure pass unchanged into the digestate [42].
- Catch crops such as Italian ryegrass or oilseed radish create strong agricultural synergies. Grown between main crops, they bind residual nutrients and prevent leaching; harvested for AD, they provide carbon-rich, non-food biomass that boosts methane yields without competing with food production. Co-digestion of catch crops with manure has demonstrated methane yield increases of up to 1.46 times compared to manure alone [43].

- **Municipal organic streams**, particularly the organic fraction of municipal solid waste (OFMSW) and sewage sludge, represent abundant feedstocks for regional AD plants. OFMSW and kitchen waste are highly biodegradable and have strong methane potential [44]. Digestates from these materials often exhibit high nitrogen and potassium concentrations, elevated pH (7.5–9), and high organic carbon [45], [46]. However, mono-digestion of food waste can destabilise the process, requiring co-digestion with manure or sludge [40]. On the other hand, municipal organic streams frequently contain plastics, microplastics, and glass [44], while sewage sludge may concentrate heavy metals, pathogens, and pharmaceuticals [42]. Nevertheless, when pre-sorting and quality control are strong, urban–rural AD integration reduces landfill dependency, increases renewable energy production, and returns nutrients back to surrounding agricultural lands.
- **Agro-food industries** include brewery spent grains, whey, fruit and vegetable processing residues, slaughterhouse by-products, glycerol, and vinasse. Industrial substrates often boost methane production due to their high Chemical Oxygen Demand (COD) content but may require balancing with manures to avoid acidification or free-ammonia inhibition. Slaughterhouse and protein-rich wastes deliver high methane potential but carry risks of ammonia toxicity [47]. Biodiesel and bioethanol residues, such as glycerol and vinasse, are powerful co-substrates that enhance biogas yields when properly dosed [39].

Co-digestion of different feedstocks allows to combine characteristics improving biogas yield and digestate quality [40], [43]. Then, AD becomes a platform through which organic waste streams are valorised locally, renewable energy is produced, and nutrient loops are closed at regional scale, creating territorial synergies between agriculture, industry, and municipalities. This means that digestate characteristics might be pre-defined by the local available feedstock, and its selection is one of the most effective and lowest-cost strategies for ensuring digestate safety, minimising contaminants, and improving fertiliser quality. Prediction of digestate characteristics allows its proper management, preventing potential impacts such as nutrient surplus, eutrophication, etc.

Nonetheless, digestate composition can still be highly variable between different biogas plants, due to differences in feedstock, AD operating conditions, dilution ratios, and post-treatment technologies [42]. This variability complicates standardisation, hinders fertiliser planning, and may affect the Nitrogen Fertiliser Replacement Value (NFRV), which tends to be higher at lower C:N ratios and lower soil pH [48]. To accurately predict digestate performance, it is necessary to quantify its chemical characteristics, especially the balance of carbon, nitrogen and phosphorus:

- Digestates with a low **carbon-to-nitrogen (C:N) ratio** consistently achieve higher fertiliser efficiency. Low C:N promotes rapid mineralisation of organic nitrogen to plant-available forms, whereas high C:N digestates, particularly those derived from lignocellulosic materials, can temporarily immobilise soil nitrogen as microbes decompose residual carbon.
- The **phosphorus-to-nitrogen (P:N) ratio** also shows a positive relationship with NFRV. This may reflect more balanced nutrient availability for crops, or it may act as a proxy for micronutrient-rich digestates, such as those derived from sewage sludge. Together, these findings highlight the importance of digestate chemical profiling to understand fertiliser performance.

### 4.1.2 *Management considerations*

Although raw digestate possesses intrinsic agronomic value, its direct utilisation is often constrained by its physical and chemical characteristics. In particular, the high content in water, bulk volume, and heterogeneous composition pose major logistical limitations for storage, transport, and field application, making further processing essential for efficient resource recovery [38], [45]. Advanced processing technologies address these limitations by transforming untreated digestate into standardized, high-value products suitable for agricultural and industrial markets. Overall, the aims of digestate processing are to (i) concentrate nutrients, (ii) reduce mass and moisture, (iii) stabilise residual organic matter, and (iv) produce consistent, market-ready biofertilizers capable of competing with conventional mineral fertilisers [47]. Liquid and solid fractions are obtained from digestate separation, one of the main post-treatments, and their management differs accordingly to their characteristics:

- The liquid fraction constitutes 80–90% of the total digestate volume and contains most of the plant-available nitrogen (as ammonium) and potassium [49]. Its rapid infiltration into soil reduces ammonia volatilisation compared with raw slurry, although careful timing is required to avoid nitrate leaching [50]. When higher concentration or export is needed, the liquid fraction is fed into advanced treatments, such as ultrafiltration, reverse osmosis, or ammonia stripping, but these processes demand very low suspended solids to avoid membrane fouling [47]. Phosphorus recovery from the liquid fraction of anaerobic digestate is technically challenging because 55–80% of total phosphorus naturally partitions into the solid fraction during mechanical separation [50], [51]. The remaining dissolved phosphate in the liquid fraction is typically low in concentration, yet can still be recovered through precipitation, membrane concentration, or biological assimilation [47]. These technologies aim to extract phosphorus from a diluted matrix and produce concentrated, transportable, and agronomically valuable fertilisers
- The solid fraction represents 10–20% of the total mass but concentrates most of the phosphorus and organic matter [49]. It acts as an organic soil conditioner, enhancing soil structure, increasing humus content, and allowing phosphorus export away from saturated livestock regions [38], [50]. The solid fraction is also the basis for post-treatments such as composting, drying, or pelletising, which stabilise the material, improve sanitary quality, and enhance marketability [52]. Composting the solid fraction of anaerobic digestate is a key post-treatment step used to enhance stability, sanitary quality, handling properties, and agronomic value. Although AD substantially stabilises the material, the solid fraction still retains biodegradable compounds and a significant proportion of organic nitrogen, which can continue to degrade and emit odours if not further treated [38], [50]. Composting serves several essential purposes. It stabilises and humifies the remaining organic matter, transforming labile compounds into stable humic substances that support soil structure and long-term carbon sequestration [38].

Despite clear chemical differences between digestate fractions, there are no significant differences in yield response between raw digestate, its liquid fraction, or its solid fraction, when all were applied at equal total nitrogen rates [48]. Liquid fractions typically contain more mineral nitrogen and have lower C:N ratios, whereas solid fractions retain more fibrous organic nitrogen. Yet these differences do not translate into statistically different fertiliser performance.

Life Cycle Assessment (LCA) studies indicate that separated digestate generally performs better environmentally than raw digestate, primarily due to lower air emissions after field application [53]. Scenarios involving advanced post-treatment exhibit significantly reduced terrestrial acidification potential (0.11–0.09 kg $SO_2$ eq compared with 0.18 kg $SO_2$ eq for untreated digestate), reflecting reduced $NH_3$ emissions during land spreading.

### 4.1.3 *Ammonia volatilisation*

Digestates have high content of plant-available ammonium-N ($NH_4^+$-N) being highly susceptible to $NH_3$ volatilisation during storage and spreading [51]. These losses reduce fertiliser value and contribute to atmospheric pollution and soil acidification [53]. However, digestate consistently performs better in acidic soils, where ammonium remains in its non-volatile form ($NH_4^+$), reducing nitrogen losses through ammonia volatilisation. In contrast, alkaline soils tend to lower digestate efficiency by promoting the conversion of ammonium to gaseous ammonia ($NH_3$), resulting in significant nitrogen loss shortly after application. Low-emission land-application techniques, such as digestate injection or trailing-shoe spreading, greatly reduce $NH_3$ losses and associated odours. Other mitigation strategy is precision feeding, adjusting the protein supply in animal diets (such in cows) lowers urinary N excretion by 28% and manure N by 19%, reducing gas emissions without compromising milk production [54].

### 4.1.4 *Unbalance of Soil Organic Matter (SOM)*

Digestate is not always fully stabilised and may contain residual biodegradable organic matter, leading to SOM unbalance, phytotoxicity, excessive salinity, or high electrical conductivity, especially in pig-manure-derived products or stripped fractions [45], [46].

The potential unbalance of soil organic matter following digestate application originates from the substantial degradation of organic matter that occurs during the AD process. During AD, a large share of the feedstock's organic carbon is transformed into methane ($CH_4$) and carbon dioxide ($CO_2$), providing renewable energy but reducing the total organic carbon (TOC) of the residue. Depending on the feedstock and operational conditions, between 20% and 95% of the original organic matter is mineralised, resulting in a digestate with markedly lower TOC and a reduced carbon-to-nitrogen (C/N) ratio compared to the input substrate [47], [55].

Because the labile carbon fraction is largely removed, digestate behaves differently from compost with respect to SOM dynamics. The scientific literature consistently classifies digestate primarily as an organic fertiliser, due to its high content of readily available nutrients, especially mineral nitrogen, whereas compost is considered an organic soil improver, characterised by higher concentrations of stable humified carbon [39], [55]. Some authors note that the application of anaerobic digestate may have a limited long-term influence on SOM levels, especially when digestates with low carbon content are repeatedly applied without complementary organic materials [55].

Although AD substantially reduces the labile fraction of organic matter, digestate can still contribute to SOM maintenance and to the stability of soil biological processes. This is largely due to the enrichment of recalcitrant organic fractions during digestion. While soluble cellular compounds and easily biodegradable substrates decrease, AD concentrates more resistant structures such as lignin and non-hydrolysable lipids [56]. These constituents degrade slowly in soil and contribute to long-term SOM formation, even if the microbial "priming effect" typically associated with raw manure is diminished when digestate has a low carbon content [55].

The long-term effect of digestate on SOM is also evident when comparing its performance with mineral fertilisers. Several long-term field studies indicate that repeated digestate application increases total soil nitrogen (Nt) and total soil carbon (Ct) relative to mineral fertiliser treatments or unfertilised controls [57],

[58]. Although digestate is less effective than compost in building SOM, it still contributes positively to soil fertility and nutrient cycling.

Several post-treatment strategies can be applied to enhance the soil-improving capacity of digestate and compensate for the loss of labile carbon during AD. One of the most established approaches is composting the solid fraction, which further stabilises the organic matter through aerobic microbial activity. This transformation produces a mature, humified material with improved structure, reduced phytotoxicity, and significant benefits for SOM accumulation and soil functionality [38], [56]. Composting thus upgrades digestate from a nutrient-rich fertiliser to an effective soil improver. Another promising strategy is the production of biochar through pyrolysis. Digestate-derived biochar is highly carbon-dense, chemically stable, and capable of long-term carbon sequestration. Its application to soil enhances fertility, increases nutrient retention, and mitigates the phytotoxic effects sometimes associated with raw digestate [59], [60]. A third pathway is hydrothermal carbonisation (HTC), which converts digestate into hydrochar at elevated temperature and pressure without requiring energy-intensive drying. Hydrochar supports SOM accumulation and provides additional benefits related to nutrient recovery and soil amendment potential [60], [61].

### 4.1.5 *Digestate as fertilizer*

Based on a comprehensive meta-analysis covering forty fertilisation experiments, the agronomic performance of digestate is best assessed through its NFRV [48]. Although digestate plays a central role in circular agriculture by closing nutrient loops and supplying organic carbon, its short-term nitrogen efficiency is consistently lower than that of mineral fertilisers. Importantly, its performance is driven by specific nutrient ratios and soil properties rather than by feedstock origin or digestate fraction. The meta-analysis reports a mean NFRV of 0.779 ± 0.126, meaning that one kilogram of nitrogen in digestate produces, on average, the same yield response as approximately 0.78 kilograms of mineral nitrogen. This confirms digestate as a relatively efficient bio-based fertiliser (Figure 4), though not a direct one-to-one substitute.

Figure 4. Application of digestate as fertilizer on the field [130]

Digestate performance, however, is highly variable. Across the full dataset, NFRV values ranged from −0.54 to 1.97. In roughly one-quarter of cases, digestate outperformed mineral fertilisers, likely reflecting situations where the addition of organic matter or secondary nutrients improved soil conditions beyond what mineral nitrogen alone could achieve. At the opposite extreme, several observations showed negative NFRV values, indicating yields lower than unfertilised controls, typically associated with nitrogen immobilisation, salinity, or phytotoxic compounds in insufficiently stabilised digestates.

### 4.1.6 *Emerging biorefinery routes*

Digestate can also serve as a feedstock for biorefinery pathways that generate high-value products beyond traditional fertilisers. Processes such as hydrothermal carbonisation (HTC), pyrolysis, and gasification convert digestate into hydrochar, biochar, bio-oil, or syngas [60]. These materials can act as soil amendments, carbon sequestration agents, or renewable fuels. Biochars derived from digestate can immobilize heavy metals and enhance soil structure [60].

The liquid fraction, rich in volatile fatty acids (VFAs), can serve as a carbon source for producing polyhydroxyalkanoates (PHAs, a biodegradable bioplastic) [47], [62]. Digestate-derived substrates also support microalgae cultivation for biofuel or feed applications [60] and solid-state fermentation processes yielding enzymes or biopesticides [63], [64].

## 4.2 Environmental impact

AD process and digestate management have an environmental impact to be considered beside the benefits from revalorize waste. The risk of spreading contaminants or eutrophication linked to already vulnerable zones are some of the main drawbacks of AD. In this section, positive and negative impacts were identified, and mitigation measures are proposed when possible.

### 4.2.1 *The paradox of Nitrate Vulnerable Zones (NVZs)*

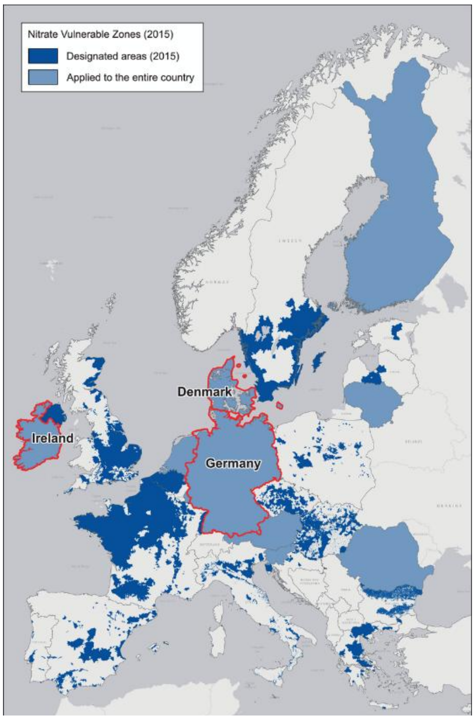

Figure 5. Nitrate Vulnerable Zones in Europe [51]

Biogas plants are typically established in regions with high concentrations of livestock, agro-industrial residues, and food waste, because these areas generate large, continuous streams of organic feedstock. This geographic logic maximises biogas production and operational efficiency, but it also creates a structural paradox: the regions best suited for biogas production are often the least capable of absorbing the resulting digestate within legal limits.

High-density livestock regions, common AD hotspots, are frequently designated as Nitrate Vulnerable Zones (NVZs) under the EU Nitrates Directive (Figure 5). In these zones, the application of livestock manure is restricted to 170 kg N $ha^{-1}$ $yr^{-1}$ to minimise nitrate leaching and protect water quality [50], [53]. Yet the very farms that supply the feedstock for biogas plants already face structural nitrogen surpluses: livestock manure, food-processing residues, and other biomasses often produce far more nitrogen than can legally be applied locally.

As a result, even though anaerobic digestion improves nutrient management by stabilising organic matter and increasing nitrogen availability, biogas plants amplify the concentration of nutrients within an already nutrient-saturated territory. Digestate therefore accumulates where land availability is most limited, creating a mismatch between where digestate is produced and where it can be legally and agronomically applied.

To resolve this spatial imbalance, digestate must be exported outside NVZs, moving nutrients from surplus regions to areas with nutrient deficits [50]. However, the raw digestate produced by AD, characterised by high content in water and low nutrient density, is economically unfeasible to transport over long distances. This limitation has driven the development and deployment of mechanical separation and advanced nutrient-recovery technologies, which reduce volume, increase nutrient concentration, and convert digestate into stable, export-ready fertiliser products [50], [51].

In this context, nitrogen export emerges not as a secondary option but as a structural necessity for the environmental, legal, and economic viability of biogas plants in livestock-intensive territories. A range of processing options exists to extract surplus nitrogen from NVZs. These technologies differ in complexity, cost, and the form of exportable products they generate, but all share the goal of increasing nutrient density while reducing transport volume.

The proposed RENURE (REcovered Nitrogen from manURE) criteria by Joint Research Centre [51] would allow certain processed materials, those functionally equivalent to mineral fertilisers, to exceed the Nitrates Directive's threshold (170 kg N $ha^{-1}$ $yr^{-1}$ within NVZs). Candidate products must have a mineral nitrogen to total nitrogen ratio (Nmin/TN) higher than 90% or a total organic carbon to total nitrogen ratio (TOC/TN) smaller than 3% [51]. Technologies such as ammonia stripping and membrane concentration typically meet these criteria, producing fertilisers that behave similarly to mineral products. By contrast, liquid fractions obtained solely through mechanical separation rarely qualify, as only 4–13% of samples meet the RENURE standard [51].

### 4.2.2 *Nitrogen leaching and water pollution*

Digestate is characterised by high concentrations of ammonium nitrogen ($NH_4^+$), that enhances its value as a fast-acting fertiliser, but it simultaneously introduces a major environmental vulnerability. Once applied to soil, $NH_4^+$ undergoes rapid microbial nitrification, transforming into nitrate ($NO_3^-$), a highly mobile anion prone to leaching into groundwater, particularly in sandy soils, under high rainfall, or when nitrogen applications exceed crop uptake capacity [65]. Excess nitrate leaching contributes to groundwater contamination, surface-water eutrophication, and non-compliance with the EU Nitrates Directive (91/676/EEC), which restricts manure application in Nitrate Vulnerable Zones (NVZs) [40], [50].

Seasonal patterns further exacerbate this risk. Autumn application of digestate, when crop N uptake is minimal, has been shown to significantly increase nitrate leaching, in some cases even exceeding the leaching associated with raw slurry due to the rapid mineralisation and mobility of digestate nitrogen [51]. Together, these hydrological and microbial processes place $NH_4^+$ management at the forefront of groundwater protection strategies in digestate-based fertilisation systems.

Given the scale of nitrogen flows in livestock-intensive regions, effective mitigation requires technologies capable of partitioning, concentrating, or recovering ammonium nitrogen prior to land application. The following sections outline the primary filtration and nutrient-recovery technologies used to reduce nitrate leaching risk and improve nutrient use efficiency.

### 4.2.3 *Phosphorous eutrophication*

The application of digestate to agricultural soils presents a well-recognised risk of phosphorus (P) eutrophication in surface waters. This risk is particularly acute in regions with intensive livestock farming, where nutrient production systematically exceeds crop uptake capacity. In such territories, repeated inputs of manure and digestate lead to structural P surpluses, which increase the likelihood of nutrient runoff and leaching, ultimately threatening aquatic ecosystems. Phosphorus-driven eutrophication arises when nutrient surpluses generated on agricultural land reach water bodies, fuelling algal blooms, decreasing dissolved oxygen, and disrupting ecological balance. Numerous mechanisms contribute to these losses:

- First, nutrient runoff is a major pathway. Digestate applications contain nitrogen and phosphorus derived from animal feed or other organic inputs, and when applied in excess or under unsuitable conditions, these nutrients can be mobilised and transported to surface waters [39], [40]. This is exacerbated in livestock-intensive regions, where manure-based fertilisers contribute to cumulative nutrient loads that far surpass crop requirements [66].
- Second, phosphorus accumulation in soils plays a central role. Organic residues such as slurries and digestates, when applied repeatedly over time, can saturate soils with phosphorus. Once soil P sorption sites are filled, the risk of P movement into water bodies increases substantially [66]. This situation is paradoxical: although global phosphate reserves are depleting, many livestock-dense regions face local P excesses, "hotspots" that pose a significant eutrophication threat [67].

Together, these factors position phosphorus management as one of the most critical environmental challenges associated with digestate application. Mechanical separation or chemical precipitation are the most widely implemented steps for P management; by concentrating phosphorus in a stackable solid fraction, it facilitates export from nutrient-saturated farms to regions with P deficits [50], [67]. Besides, microalgal systems can assimilate up to 91% of P from the liquid digestate [40]; however, high turbidity and elevated ammonia concentrations in digestate limit scalability and may necessitate pre-dilution or pre-treatment [60].

Phosphorus management has significant environmental and economic consequences. LCA studies indicate that restricting digestate land application without enabling nutrient recycling paradoxically increases environmental impacts, including freshwater eutrophication by up to 300%, due to reliance on alternative disposal routes [53]. Conversely, substituting mineral fertilisers with digestate or digestate-derived products can reduce eutrophication potential by lowering the nutrient runoff associated with industrial fertiliser use [40].

### 4.2.4 *Reduction of GHG emissions*

Greenhouse gas emissions from intensive livestock systems arise mainly from manure management, digestate handling and the manufacture of synthetic mineral fertilizers. AD mitigates these impacts through three converging mechanisms:

- A primary mitigation benefit of AD arises from fossil fuel substitution. Biogas generated during digestion displaces fossil-derived energy in heat and electricity production, representing one of AD's largest contributions to $CO_2$ reduction [38], [68].
- In parallel, methane avoidance plays a crucial role: diverting manure from open storage to digesters prevents the uncontrolled anaerobic decomposition responsible for large $CH_4$ emissions [40]. AD also reduces emissions linked to agro-industrial waste disposal by stabilising biodegradable material before treatment [40].
- A third key pathway is fertiliser substitution. Digestate-based fertilisers can replace up to 12% of synthetic nitrogen inputs [55], and their life-cycle emissions are consistently lower than those of mineral fertilizers [69]. Reported mitigation values range from 2–12 kg $CO_2$-eq per kg N applied [68],

[69] and 27.9–61.6 kg $CO_2$-eq per Mg of digestate [40]. Although variable across systems, these studies highlight the substantial GHG reduction potential of digestate recycling.

Collectively, these processes reduce emissions of $CH_4$, $CO_2$, $N_2O$ and $NH_3$, making AD a cornerstone of climate mitigation strategies in manure-intensive regions.

## 4.3 Biodiversity

The influence of AD on biodiversity in farmed landscapes largely depends on how digestate is handled. Both positive and negative impacts are possible, with outcomes strongly shaped by local environmental conditions and management practices.

### 4.3.1 *Lower biological pressure*

Farmers have traditionally applied raw slurry and manure as fertilizers. Compared with these materials, digestate can supply nutrients more efficiently, helping to reduce reliance on synthetic fertilizers and resulting in more regulated plant growth [70]. It also contains fewer pathogens and markedly fewer viable weed seeds than untreated slurry, which limits weed spread during land application and may reduce the need for herbicides [71]. Depending on the temperature of the AD process, the sanitation level of digestate can achieve more than 99% inactivation of pathogens such as *Salmonella* and *E. coli* [72] and effectively destroys many weed seeds [71]. Nonetheless, digestate may still contain bacteria, viruses, and parasites capable of surviving land application, persisting in soil, and entering the food chain [73].

The European Union has established stringent microbiological criteria governing the use of digestate as a fertilizer. Regulation (EU) 2019/1009 and associated Animal By-Products rules require: (i) absence of Salmonella in 25 g of product, (ii) fewer than 1,000 CFU $g^{-1}$ of *E. coli* or *Enterococcaceae* in fresh mass and (iii) compliance with hygiene and sanitisation standards equivalent to pasteurisation. Some national or voluntary quality schemes also restrict viable weed seeds (e.g., <2 seeds per litre). Despite these standards, the risk of post-treatment regrowth, especially of *Clostridium* spores, and the influence of storage conditions necessitate ongoing vigilance. Application methods such as soil injection rather than surface spreading help minimise human and crop exposure by reducing aerosolisation and environmental dissemination [42], [73].

### 4.3.2 *Effects on soil microbial communities*

Digestate can function as a soil amendment that boosts crop productivity, in part because it carries microorganisms capable of further breaking down organic matter and releasing nutrients [38]. However, its chemical and microbial makeup can also influence soil biota, particularly microbial populations. A study showed that the response of soil microorganisms varies by soil type: microbial biomass declined by roughly 40% ($P < 0.001$) in coarse-textured soils such as loam and sandy loam, while fine-textured soils showed no significant change [74]. Bacterial diversity remained stable across soil types ($P > 0.05$), but fungal diversity increased by about 35% ($P < 0.001$) in soils with low C/N ratios (average 9.14). These findings highlight that soils with different textures and microbial communities react differently to specific digestates [74]. Given the crucial role of soil microbiota in nutrient cycling and crop production, more research is needed before large-scale agricultural use of digestate to ensure long-term soil health.

### 4.3.3 *Risks of eutrophication and contamination*

If digestate is over-applied or poorly managed, it can contribute to nutrient losses, especially nitrogen and phosphorus, which promote soil acidification and aquatic eutrophication [53]. Excess phosphorus is a major driver of eutrophication in freshwater systems, often leading to ecosystem collapse and loss of fish populations them [75]. Nitrogen, mostly leached as nitrate, can move through soil into groundwater used for drinking water, creating risks for human health [76].

Digestate can also contain contaminants carried over from biogas feedstocks, including heavy metals, plastics, pathogens, and emerging pollutants such as dichlorobenzene compounds [53]. Although many contaminants occur at low concentrations, they can accumulate over time in soil and groundwater:

- Heavy metal concentrations in organic fertilizers are typically within European regulatory limits [77], but elements like cadmium and zinc may be elevated in the liquid digestate fraction, similar to levels in untreated manure or sewage sludge [53]. Even concentrations considered acceptable by European regulatory limits (45 mg Cd·$kg^{-1}$ P) can still result in long-term soil accumulation [78]. Moreover, most metals tend to associate with the solid digestate fraction, concretely to organic matter, hence the solid fraction carries most of the long-term soil contamination risk. Because metals are persistent and do not biodegrade, their accumulation is effectively irreversible without costly remediation. Soil pH plays a critical role in determining metal bioavailability. Acidic soils tend to increase metal solubility, thereby enhancing uptake by plants and increasing phytotoxicity risk. Metals can also be mobilised toward water bodies through leaching or surface runoff, especially in permeable soils or under conditions of heavy rainfall [42].

  The proposed RENURE criteria introduce additional limits to the European regulation, such as Cu ≤ 300 mg/kg DM and Zn ≤ 800 mg/kg DM [51]. Approximately 95% of digestates originating from co-digested manure appear to comply with these proposed limits. Regulations vary internationally: the United States Environmental Protection Agency (EPA Part 503) allows considerably higher tolerances for certain metals, prioritising the beneficial reuse of biosolids [42]. In contrast, countries such as Denmark and the Netherlands impose stricter limits to minimise long-term soil accumulation [53].

- Plastics are introduced in the biowaste stream due to improper segregation at source, during mechanical pre-treatment these plastics are fragmented into microplastics (<5 mm diameter). Because these particles are resistant to degradation under anaerobic conditions and difficult to remove after fermentation, they persist in the digestate [44]. Increasing reliance on biowaste as a substrate has been linked to the rising introduction of microplastics into digestate [42]. Concentrations vary widely depending on feedstock quality and plant operations: raw digestate has been reported to contain between 41 and 3,298 particles per kg (wet weight), while solid digestate shows even higher concentrations, ranging from 319 to 3,604 particles per kg [42]. When digestate containing these contaminants is applied to agricultural soils, microplastics accumulate and can exert long-term ecological and human health effects. The European Union only regulates macroscopic physical impurities (>2 mm), restricting them to ≤0.5% of dry matter, but does not regulate microplastics specifically [44]. This regulatory gap persists largely because of technical obstacles: microplastic detection in digestate is difficult, labour-intensive, and expensive, especially for particles smaller than 2 mm. Advanced detection techniques such as FTIR spectroscopy and Raman microspectroscopy provide reliable identification but are not widely deployed in routine quality control in waste management facilities [44].

Contaminant buildup from various industrial activities represents a global environmental issue, made worse by limited use of hygienization and pre-treatment processes in many sectors [40]. Incorporating such treatments into AD systems on farms is therefore vital to ensure that digestate can be safely applied to agricultural land. Most treatments for metal contamination consist of metal immobilisation, through pyrolysis of digestate into biochar [79] or using humic substances [61]. Nonetheless, the most effective method to control contaminants in digestate remains being the source control.

## 4.4 Social impact

From a social perspective, the expansion of AD in farming regions is strongly influenced by how communities perceive its risks and by concerns about land use. Supportive policies and effective outreach are essential for wider adoption, after which AD can contribute meaningfully to rural development.

### 4.4.1 *Land competition and energy cover crops*

Using edible crops for energy generation remains controversial due to the risk of displacing food production. To prevent such conflicts, the European Union's Renewable Energy Directive (2018/2001) sets sustainability criteria requiring that biomass for energy must not come from areas rich in biodiversity or from soils with high carbon stocks [80].

Several European countries are therefore considering substituting dedicated energy crops with energy cover crops for biogas. These crops are not grown as cash crops and generally do not interfere with food production because they occupy short growing windows when food crops cannot be cultivated. However, this interval is increasingly being used for additional forage production [81] and, in some climates, even food crops [82]. Although cover crops are already encouraged, particularly in nitrate-vulnerable zones, because of their environmental benefits and their role in reducing nitrogen leaching (European Union Nitrate Directive 91/676/EEC), expanding their use for energy purposes raises some challenges [80]. Achieving sufficient biomass yields is necessary for economic viability, and energy cover crops typically demand more intensive management and inputs such as water and fertilizers than conventional cover crops. For this reason, cropping systems should be designed to maximise the environmental services provided by energy cover crops while allowing farmers to earn supplemental income and enhance long-term soil quality (e.g., higher organic matter, stronger soil structure, reduced pest pressure) [80].

### 4.4.2 *Technical employment and rural development*

Small-scale AD development in agricultural settings has been hindered by limited practical experience and few specialized companies, which restricts access to qualified support when technical issues arise [83]. Uneven training among developers and operators has occasionally resulted in poorly designed or maintained facilities, some of which were ultimately abandoned due to mechanical failures, design flaws, or operational breakdowns [84], [85]. Many difficulties emerge in the early operational phase because of the challenge of predicting real-world performance [86]. To strengthen AD deployment in agriculture, incentives and support mechanisms are needed to stimulate sustainable rural growth. Once established, AD can provide skilled job opportunities in farming regions.

In addition, AD can create new revenue streams for farmers, not only through on-site biogas or biomethane production but also through feedstock collection and supply chains. Better financial prospects may encourage younger generations to enter or remain in the agricultural workforce, supporting the long-term resilience of the sector [83].

### 4.4.3 *Public acceptance of feedstock sourcing*

AD offers a way to redirect organic wastes, such as food waste and slurries, away from landfilling or conventional composting. Improved waste management also cuts greenhouse gas emissions associated with these traditional practices. When treated as AD feedstocks, organic wastes become a source of renewable energy and valuable by-products, supporting a more circular economic model [83].

At the European legislative level, digestate is defined as a waste according to the European List of Waste included in the Commission Decision of 3 May 2000. In 2013, the Joint Research Centre (JRC) of the European Commission published the study *End-of-waste criteria for biodegradable waste subjected to biological treatment (compost & digestate): Technical proposals*, which sets out the criteria that, according to the JRC, should be established in European legislation to determine when digestate ceases to be classified as waste. Hence, the new Fertilising Products Regulation, Regulation (EU) 2019/1009, establishes the criteria under which digestate may cease to be considered waste if it forms part of an EU fertilizing product.

### 4.4.4 *Grid connection and gas lose*

Another challenge for agricultural AD projects is securing a grid connection. Regulatory barriers, connection fees, and complex licensing requirements can be costly and difficult to navigate, causing some operators to flare surplus biogas [84], [87]. Grid systems are often built for large energy producers and may not be well suited to small-scale installations [83]. Connection costs are highly dependent on both the distance to the nearest substation and its available capacity [86]. Reliable grid access, or adequate gas-storage capacity, is essential to prevent gas losses that undermine the environmental benefits of AD. Facilitating easier and more affordable grid connections would help reduce these losses and encourage broader adoption among farmers.

### 4.4.5 *Odour and toxic gases*

Strict regulations on leachate, odour emissions, and toxic gases exist across most countries, strengthening the case for AD relative to other waste-treatment methods [87]. Key air pollutants associated with AD include hydrogen sulphide, ammonia, and siloxanes, along with fugitive methane and carbon dioxide released during digestion or digestate storage [88]. However, because AD occurs in sealed reactors, these emissions are typically easier to manage than those from composting, landfilling, or incineration, which involve more open processes and higher management costs [88]. The extent of odour reduction is especially important where farms are located close to residential areas [83].

Studies show that applying digestate rather than raw slurry or livestock manure significantly reduces odour levels in the air [89]. This is largely because digestate contains fewer volatile fatty acids (VFAs), phenols, indoles and other odour-generating compounds [90]. During AD, these molecules are degraded by 20–95% of the readily degradable organic matter [38]. As VFAs are consumed, the digester pH rises, a typical indicator of odour reduction [40]. These biochemical transformations explain why AD-based systems release substantially fewer odorous emissions than unmanaged or aerobic degradation systems.

# 5. ONSHORE WIND ENERGY IMPACTS IN AGRICULTURE

Wind power is emerging as an energy source within agriculture, supporting activities such as irrigation, greenhouse operation, and a variety of on-farm processes (Figure 6). Adoption rates, however, differ widely. Many farmers choose to rent out their land for turbine installation instead of investing in wind systems themselves [91]. Although wind energy has shown strong performance in recent years, it still produces certain environmental and social impacts, generally minor when compared with other renewable or fossil-based energy options [91], [92]. This section outlines the key limitations associated with integrating wind technologies into agricultural systems and suggests mitigation strategies that can support long-term, profitable, and sustainable agro-energy setups.

Figure 6. A 10 kW turbine on 140-foot freestanding lattice tower for residential and/or agriculture use [131]

## 5.1 Agronomic impact

Wind turbines can alter local airflow patterns, creating microclimates that may not suit all crop types. Variations in wind velocity and turbulence levels require farmers to carefully evaluate which crops can thrive near turbine installations. Equally important is the choice of turbine technology, as different designs influence both energy output and agricultural conditions.

### 5.1.1 *Design-related impacts: wake effects*

Current wind technologies include small wind turbines, either vertical or horizontal axis blades (of up to 10 m of rotor diameter), as well as emerging bladeless systems (based on the vortex induced vibration approach), and large wind turbines (>10 m of rotor diameter with horizontal axis blades) [93], [94]. Bladed turbines introduce turbulence into the air column, whereas bladeless designs do not generate this effect [94]. Turbulent wakes can modify local atmospheric behaviour by enhancing vertical air mixing. These altered airflow patterns typically decrease wind speed near the ground and increase turbulence, which can accelerate evaporation. Wake characteristics depend on multiple variables, including wind speed, prevailing wind direction, atmospheric turbulence, and turbine operation parameters [95]. Wind turbines are engineered to match the characteristics of their installation site, in order to optimize energy yields and reduce the wake effect loss. Therefore, the efficiency of a wind turbine and its local impact are closely linked [91].

The magnitude of wake-related losses is tied to turbine dimensions and design, which are shaped by factors such as land availability, wind resource quality, and location-specific constraints. Larger wind turbines are the most common, they produce more energy but also have more environmental impact [96]. Selecting the most suitable turbine type for an agricultural landscape requires detailed site assessments that consider crop height, roughness length, and other land-surface properties [97]. For instance, in a large-scale wind farm, shifting surrounding crops from maize to soybeans, crops with different canopy structures, has been estimated to increase power generation by 14% [98].

Research on the agricultural implications of wind projects remains limited, especially for small-scale systems. Existing studies mostly address large wind farms. For example, [99] found no effects of large-scale wind farms on plant quality and biodiversity, five years after turbines installation. Conversely, [100] reported long-term declines in soil moisture after 14 years, which affected plant communities; similar findings show long-term alterations in local atmospheric conditions around large installations [95]. These studies indicate that large turbines can influence soil and vegetation over time.

Mitigation strategies include careful spatial planning, appropriate turbine sizing, and adaptive management of both the energy system and crop selection. Choosing crops that are tolerant of lower moisture levels may help offset increased evaporation near turbine wakes. Nevertheless, significant knowledge gaps remain regarding the effects of small-scale wind systems, likely the most feasible option for individual farmers aiming to integrate onsite renewable energy into their fields.

### 5.1.2 *Altered air temperature and $CO_2$ fluxes*

Large wind turbines can alter air temperature and CO2 fluxes through their wakes, this can affect local surface conditions. For instance, mixing generated by turbines can disrupt nocturnal temperature inversions, leading to warmer nighttime surface temperatures [101]. The temperature increases observed near wind farms, typically between 0.7 and 3.5 °C [102], [103], are large enough to meaningfully affect carbon cycling and plant growth in many ecosystems [104]. For example, in a subarctic peatland, a warming of about 1 °C increased respiration by 60% in spring and 52% in summer [105]. Temperature strongly regulates carbon cycling in terrestrial ecosystems; shifts in thermal conditions generally enhance plant productivity, accelerate the breakdown of organic matter, and affect the emission and uptake of $CO_2$ and $CH_4$ [105], [106]. Beyond these immediate effects on photosynthesis and decomposition, temperature changes can also alter the length of the growing season, thereby influencing overall carbon dynamics by boosting productivity and, through greater litterfall and root inputs, potentially stimulating decomposition [107].

Over short time scales, turbines may enhance carbon uptake during the daytime by increasing $CO_2$ movement into crop canopies, while also promoting negative effects such as higher nighttime respiration because of warmer temperatures. Nevertheless, substantial variability among fields, arising from differences in crop variety, soil properties, moisture availability, and management, makes it difficult to attribute whole-season biophysical responses or yield outcomes solely to turbine effects [101].

### 5.1.3 *Lower water use compared to other power plants*

Clean water is an increasingly scarce resource, and many power generation technologies rely heavily on it. Wind energy stands out as the least water-intensive option, requiring only about 0.64 L/kWh when both direct and indirect consumption are considered, slightly below even the most water-efficient fossil-based system, the natural gas combined cycle at 0.7 L/kWh [108] Fossil fuels in general consume far more water, often exceeding 1.6 L/kWh when accounting for direct use alone [92]. Consequently, integrating wind energy can ease pressure on freshwater resources, allowing more water to be allocated for agricultural needs such as irrigation. This can help counterbalance the moisture losses that may occur due to turbine-generated wake effects.

### 5.1.4 *Shading effects*

The shadows cast by turbine structures can reduce the sunlight available to nearby vegetation, potentially limiting photosynthesis and lowering crop productivity. These shaded zones originate mainly from the turbine tower. Common tower designs include monopole, guyed lattice, and lattice structures [109]. Large monopole towers, typical of utility-scale turbines, produce more pronounced shadow areas because of their size. In contrast, small turbine towers are narrower and create minimal shading, and lattice-type designs diffuse shadows more broadly than the solid silhouette of a monopole. However, lattice towers may encourage bird nesting, and guyed towers require more land due to their support cables. For agricultural landscapes, small monopole or lattice towers tend to be the most suitable, as they minimize shading impacts and avoid secondary issues linked to tower design.

## 5.2 Environmental impact

Beyond their influence on crops themselves, wind energy installations can affect soil conditions and broader local ecosystems. These effects are more pronounced for large-scale turbines. Biodiversity-related impacts are addressed separately later.

### 5.2.1 *Changes in local climate*

A widely noted environmental effect of wind farms, discussed earlier under wake dynamics, is the alteration of soil moisture. Long-term observations show that extensive wind developments can increase evaporation and reduce soil moisture, not only adjacent to the turbines but even up to 20 km away [100]. Yet, the climatic influence of wind farms varies by region. For example, a 62-season climate model simulation suggested that turbine operation might raise precipitation by roughly 1%, which would theoretically enhance soil moisture [110]. Because these trends differ across locations, ongoing monitoring of soil moisture is essential to understand site-specific impacts and to implement measures that prevent soil degradation.

### 5.2.2 *Forest fragmentation and soil degradation*

Large wind farm construction often necessitates access roads and transport routes, which can break up forested areas. Heavy machinery used for turbine delivery and installation can also compact soil, reducing its suitability for cultivation. These disturbances tend to diminish vegetation cover and can heighten soil erosion risks [111]. Although small wind turbines usually require lighter equipment and narrower access paths, they still introduce some degree of soil and habitat disruption, albeit to a far lesser extent than large-scale installations.

## 5.3 Biodiversity

Wind turbines can influence the diversity of both plant and animal species, mainly through noise and ground vibrations. Below is an overview of research examining how key groups of organisms respond to wind energy installations.

### 5.3.1 *Air-dwelling animals*

Figure 7. Dead bird, possibly killed by collision with wind turbine [132]

Concerns are frequently raised about the impact of turbines on birds and bats, particularly when wind farms are placed in or near natural habitats. Evidence indicates that many bird species rapidly learn to navigate around turbine structures, suggesting that turbines themselves pose a relatively minor threat [112]. Although bird mortality does occur (Figure 7), the number of deaths attributable to turbines is extremely small compared with losses caused by larger-scale human activities such as deforestation and urban development, even under scenarios of expansive wind-energy deployment [113]. Protective measures are also available; for example, modifications to tower lighting and design can reduce attraction and nesting opportunities [92]. In Texas, one wind project employs avian radar systems capable of detecting incoming birds and automatically shutting down turbines when collision risk is high [113].

Insects, particularly pollinators, have also been studied. A recent investigation assessed how honeybee colonies responded to turbine presence by monitoring queen egg-laying rates, colony growth, forager behaviour, and navigational abilities. Results showed no evidence of increased forager mortality, impaired reproduction, disrupted orientation, or negative effects on colony development or functioning [25].

### 5.3.2 *Ground-dwelling animals*

Subsurface vibrations produced by wind turbines can affect soil fauna, particularly species that are sensitive to low-frequency waves. Large-bodied soil invertebrates such as earthworms (>1 cm) are especially vulnerable because turbine-generated vibrations can travel considerable distances through the ground. In organic crop fields in the Netherlands, vibrational noise from large turbines decreased by approximately 23 ± 7 dB within 200 meters of the structures. Correspondingly, earthworm abundance declined by about 40% with increasing vibrational intensity, an effect that may be compounded by soil compaction during turbine installation. Since earthworms play vital roles in processes such as nutrient cycling, carbon storage, and water infiltration, reductions in their populations may have broader ecological consequences [115]. These findings highlight the need for strategies to limit ground vibrations, including innovations in turbine foundation design.

Larger animals have also been examined. For example, researchers studied whether wind farms disrupt habitat structure for the endangered European hamster (*Cricetus cricetus*). Burrow counts were conducted near turbines (up to 150 m), at intermediate distances (200–500 m), and outside of wind farms (1–5 km). The study found no indication that turbine presence caused habitat fragmentation or altered the hamsters' spatial distribution [116].

## 5.4 Social impact

Wind turbines can influence nearby communities, mainly through noise and visual presence, which some residents may find disruptive. These effects generally lessen with increased distance from homes. The following subsections summarize the primary social considerations in areas close to turbine installations.

### 5.4.1 *Mechanical and aerodynamic noise*

Turbines generate sound through both their moving machinery and the airflow over the blades. At approximately 60 meters from a turbine, measured noise levels typically range from 40 to 56 dB, comparable to the hum of a household refrigerator [92], [117]. Low-frequency aerodynamic noise in particular can disturb sleep and potentially affect hearing among people living very near wind developments. Proposed solutions include siting turbines at least 2 km from residential areas or improving building insulation to reduce noise infiltration [118]. Blade redesigns have also been suggested to reduce sound emissions without compromising aerodynamic performance [119].

### 5.4.2 *Visual impact and shadow flickering*

Visual effects are among the most subjective aspects of wind energy, with opinions varying widely: while some individuals view turbines as aesthetically pleasing, others find them intrusive. Survey data from the UK suggest that more than 70% of respondents do not hold negative views toward wind turbines [91]. Several tools, such as the Quechee Test, multicriteria evaluations, and the Spanish method, have been developed to assess visual impacts, and the Spanish method has been associated with improved public acceptance [120].

Shadow flicker, another visual disturbance, occurs in two main ways: shadows cast by rotating blades and intermittent reflections of sunlight off turbine surfaces. These phenomena can be bothersome for residents when shifting light patterns move across homes or land. Mitigation strategies include using low-reflectivity blade coatings, smoothing rotor surfaces, and installing automated control systems that temporarily shut down turbines during times of high flicker intensity, such as sunrise or sunset when shadows are longest [92].

### 5.4.3 *Social perception*

Overall, public attitudes toward wind turbines tend to be favourable. Farmers who adopt wind energy often highlight benefits such as reduced energy costs and additional income from selling surplus power when connected to the grid [109]. Leasing land for turbine installation and supporting technological innovation were also viewed positively. Nonetheless, concerns remain, particularly noise and perceived degradation of the landscape. Ultimately, the most influential factors in farmers' decisions to invest in wind energy are the long-term financial commitment and the limited availability of subsidies [121].

### 5.4.4 *Electromagnetic fields (EMF)*

A commonly mentioned concern is the potential for wind turbines to interfere with telecommunications or radar systems due to electromagnetic fields. Like all electrical generation equipment, turbines do produce EMF, but measurements show these levels are very low at the tower base (around 0.9 mG) and fall to background levels (0.2–0.3 mG) within roughly two meters [122] Homes located over 500 meters away registered external EMF levels at or below 0.4 mG. These values are significantly lower than those produced by many everyday household devices and remain well under established health guidelines [122].

# 6. BIOENERGY IMPACT IN AGRICULTURE

Biomass energy or bioenergy is a renewable resource derived from organic materials such as biomass from forests, biomass from agriculture, and organic waste. Bioenergy can be obtained through biochemical processing of biomass, i.e. anaerobic digestion, or thermochemical processing. Impacts of integration of anaerobic digestion into farms was assessed in section 4. BIOGAS PLANT IMPACTS IN AGRICULTURE. The current section is focussed on impacts from the thermochemical processing of biomass, this includes biomass combustion, pyrolysis, hydrothermal processing, and gasification. Herein is evaluated the potential impacts of bioenergies (from thermochemical processes) into the agricultural sector, highlighting mitigation strategies that can support a sustainable co-production of food and energy.

## 6.1 Agronomic impact

Bioenergy plays a valuable role providing a steady and controllable renewable source that complements variable wind and solar sources (Figure 8). Its importance has grown alongside rapid population growth and rising energy demand since the industrial revolution, often without a long-term sustainable resource strategy. It contributes to decarbonisation by enhancing carbon uptake by biomass resources while substituting fossil fuels. A key requirement is that biomass growth must be higher than bioenergy demands, to enhance carbon sequestration [123]. This means that bioenergy can create notable pressures if not managed carefully, such as carbon flow imbalances, resource competition, soil erosion, etc.

### 6.1.1 *Impact of biomass and carbon balances*

Carbon emissions from biomass are part of the continuous flow of carbon between the biosphere and the atmosphere. Although thermochemical processing of biomass for energy production can accelerate this process, accumulating $CO_2$ in the atmosphere, this is why bioenergy production must be highly controlled. To keep the carbon-flow balance, it is necessary to ensure biomass growth rate and carbon uptake levels higher than $CO_2$ emissions. Enhancing biomass-use for energy production would improve biomass management, which paradoxically would increase carbon sequestration and reduce the risk of carbon losses due to wildfire, diseases or insect outbreaks [123].

In the last years, better forest management showed to reduce wildfire risks, this management consists of biomass removal (forest debris and excessive straw), which is one of the main sources for bioenergy. About 45% of the used woody biomass in Europe is for energy production, increasing on average 3.3% every year. From this amount of wood, the 44% is dedicated wood, i.e. grown only for energy purposes [124]. Despite the increasing trends, studies reported the total harvest of woody biomass (for several uses, not only energy) amounts on average the 63% of the forest growth rate (444 Mt wood per year). Although, reported harvest is underestimated, thus the real amount is likely to be up to 12% higher. Even so, authors agree that forests in EU are still growing faster than being consumed, however this growth rate is slightly declining due to ageing of forests [125]. A practice that promotes tree growth is coppicing or coppice forests, this is a traditional management practice that consists of cutting down a tree to a stump, in which new shoots grow up, thus ultimately regrowing the tree up to 5 times faster. However, excessive coppicing may expose soil to erosion conditions and nutrient depletion, leading to soil degradation.

Therefore, bioenergy can serve as a side-energy source, complementing other RES and providing stability to the renewable energy system, while atmospheric carbon is sequestrated. However, its sustainability depends heavily on responsible land-use practices, excessive harvest (of both dedicated biomass and residual biomass) or insufficient biomass growth would produce carbon-flow imbalances and soil erosion, offsetting their benefits.

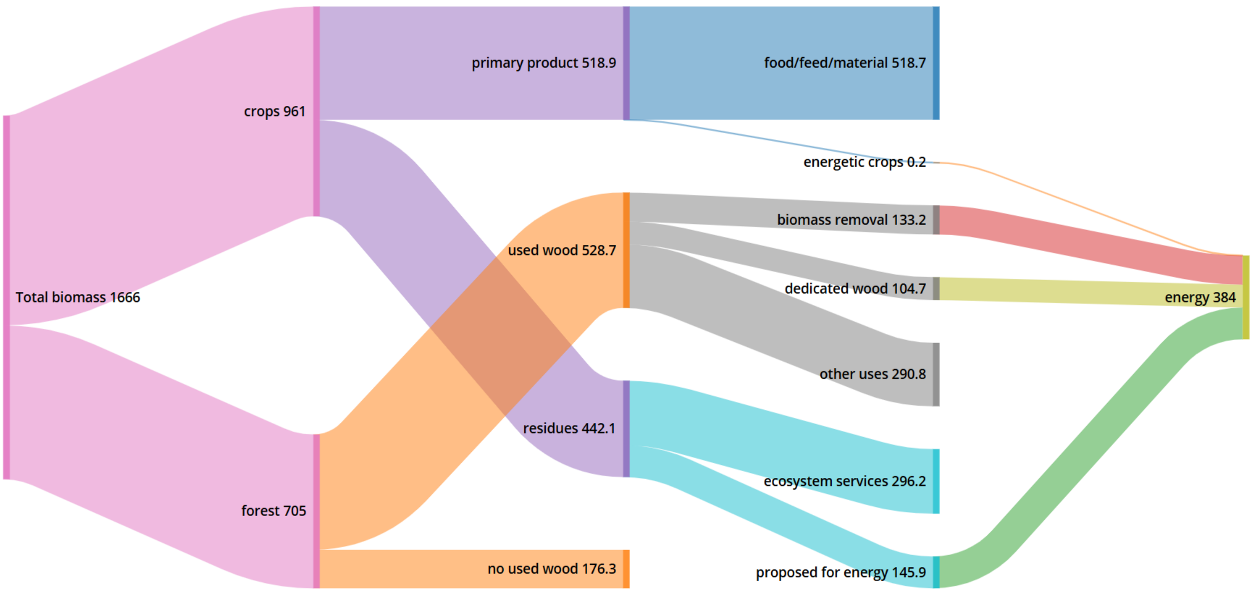


Figure 8. Sankey diagram of plant biomass produced in EU (Mt/year) and its potential use for bioenergy production.

### 6.1.2 *Land and feedstock competition*

Forests occupy 41% of the EU land area [126], no data on forests areas dedicated to energy production are reported, but 19Mha (12% of total forests) are coppice forests, which are particularly important for bioenergy (Figure 9). Hence, it is estimated that at least half of the coppice forests are used for energy production in EU [127]. On the other hand, the agricultural sector occupies the 22.5% of the EU land area [126], again no data on area of energy crops are reported, but its production in weight represents the 0.04% of the agricultural primary production in EU [125]. Considering this, area dedicated to bioenergy production can be roughly estimated to sum up to 2.47% of the total EU land area, which is outcompeted by the 61% from forests and crops dedicated to other purposes (food, feed, material). Moreover, crop land-uses practically did not change since 2005 [128], this can be explained by the large amount of forestry and agricultural residues that can supply bioenergy demands [129], not requiring extra land for dedicated biomass culturing.

Nonetheless, the increasing tendency of bioenergy demand may require more biomass in the future, this might enhance especially the feedstock competition between the different uses of biomass, such as food, feed, materials, and bioenergy. Availability of sustainable biomass as feedstock for bioenergy production should be considered. The Directive 2008/98/EC established policies that follow the principles of the circular economy and the waste hierarchy, to avoid unnecessary impacts on raw material markets. When deciding how biomass should be prioritised, factors such as social value, conversion efficiency, and greenhouse gas emission reductions must be taken into account, and the sequential use of biomass for several applications can be applied. For this reason, bioenergy is rather produced from waste and residue streams, such as crop leftovers, manure, or organic municipal waste.

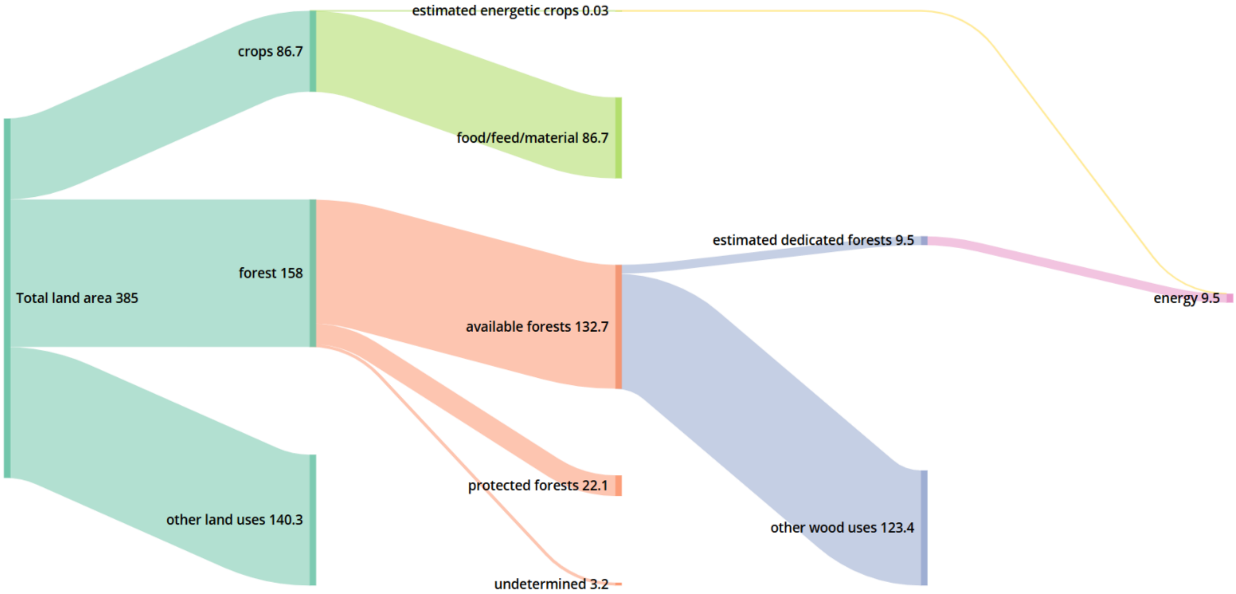


Figure 9. Sankey diagram of land use in EU (Mha) and its potential use for bioenergy production.

## 6.2 Environmental impact

Intensive harvesting of biomass for bioenergy production can reduce carbon stocks, disrupt soil health, and generate air pollutants such as particulates and nitrogen oxides, which require appropriate control technologies [125]. The overall climate benefit of biomass depends strongly on sustainable sourcing practices, efficient conversion technologies, and limited transport distances.

### 6.2.1 *Soil erosion*

Some forest management practices such as coppicing might expose soil to erosion and biodiversity lose, as well as intensive agricultural management. On the other hand, using agro-forest residues might release the environmental pressure of land-intensive practices. The 46% or 442 Mt (dry matter) of the agricultural biomass produced annually in EU is not the primary product, these 'residues' can be revalorised as animal bedding, for ecosystem services, energy production, etc [125]. Therefore, the use of agricultural residues for bioenergy production may compete with other applications. Due to this competition, ecosystem services such as maintaining soil organic carbon and prevention of soil erosion can be neglected, though they are necessary to keep a good agricultural production in long-term. Currently, the number of agricultural residues used for energy production in EU is uncertain, but it is estimated that a potential amount of 146 Mt/year (33% of annual residues) could be used to produce about 2300 PJ/year of gross energy, while accommodating competitive uses and soil organic carbon preservation [129].

Therefore, agricultural residues are theoretically able to provide a substantial amount of energy in a sustainable framework, being about 3.2% of the annual EU consumption and/or the net consumption of the agricultural sector without consider transport [130]. Excessive harvesting and mismanagement of agricultural residues in favour of bioenergy production may lead to soil erosion. Hence, the sustainability of bioenergy within agricultural systems relies again on responsible land-use practices to prevent soil degradation. The use of perennial crops, even its combination within a complex agro-forest system, can mitigate soil erosion while provide new incomes besides wood feedstock.

### 6.2.2 *Forest exploitation*

The increasing tendency of bioenergy demand may require more biomass in the future, this might produce land-use and feedstock pressures. However, authors defend that this will stimulate responses such as afforestation, reduction of deforestation rates, as well as restoration of degraded or unproductive forestland, such as abandoned coppice forests [131], [132], [133], [134]. It seems reasonable that, to maintain feedstock sources (to accommodate competitive uses and soil health), further raw biomass needs to be used. This means to make use of unexploited forests or, indeed, to increase the wood stock of exploited forests, which can be done extensively (potentially creating land-use competition) or intensively (increasing wood density through forest management with potential risk of soil-nutrient depletion and water drainage). Land-use changes have great impacts, as it directly alters habitat conditions. Therefore, best practice remain being, first of all, the use of agro-forest residues, whose biomass removal from forest can be extended further than currently; secondly, better management of exploited forests, even implementation of complex agro-forest systems to combine agricultural and forest production; and finally, in case of increasing forest extension, matching forest plantation with soils with nutrient excess, such as nitrate vulnerable zones (NVZ), to restore them.

### 6.2.3 *Air pollution*

Thermochemical bioenergy conversion processes can contribute to air pollution through the release of particulate matter, nitrogen oxides, sulphur oxides, carbon monoxide, volatile organic compounds, and other pollutants. The type and quantity of emissions depend on factors including the biomass feedstock, moisture content, combustion efficiency, and emission control technologies used. Incomplete combustion and the use of low-quality biomass can significantly increase pollutant emissions, potentially affecting air quality and human health, particularly in areas close to bioenergy facilities [135]. Although bioenergy is often considered a renewable alternative to fossil fuels, inadequate management may reduce some of its environmental benefits. Therefore, the implementation of efficient combustion systems, proper feedstock preparation, and air pollution control technologies is essential to minimise atmospheric emissions and improve the sustainability of bioenergy production.

### 6.2.4 *Impact of energy carriers*

Biomass has a very variable composition, high moisture content, and relatively low energy density (7–17 MJ/kg of dry biomass). As a result, larger quantities must be transported, handled, and stored compared with conventional fuels, making logistics more challenging. Pre-treatment processes can convert raw biomass into energy carriers such as pellets, which are easier to transport, store, and use in thermochemical conversion systems. However, these treatments can be costly and to have low-conversion efficiencies for small-scale installations typically accessible to farmers. Although larger plants are generally more cost-effective, their size is often constrained by the local availability of feedstocks, which may sometimes need to be imported [136]. The energetic consumption and gas emissions from pre-treatments, transport and feedstock management need to be considered to evaluate the environmental impact and profitability of bioenergy. Limiting transport distances and promoting local chains should be prioritized.

## 6.3 Biodiversity

The effects of bioenergy production on biodiversity are influenced by the original land use, the type of production system, and the surrounding landscape structure. Among these factors, land use change has the greatest impact, as it directly alters habitat conditions and management practices. The extent of these effects also depends on the plant species used and the location where they are cultivated [135].

### 6.3.1 *Habitat degradation*

At present, only about 2–4% of forests in the EU are considered primary forests with little or no human disturbance, while approximately 89% are classified as semi-natural forests and the remainder are plantations. Forest cover in the EU increased by around 13 million hectares between 1990 and 2015 as a result of both natural expansion and afforestation efforts. However, this increase in forest area does not necessarily reflect an overall good ecological condition. Most EU forests (around 84% of forest land) are managed as Forest Available for Wood Supply, whereas only about 14% are primarily protected for biodiversity conservation. According to assessments under the Habitats Directive, only 14% of forest habitats are in favourable conservation status, while 54% are considered poor, 31% bad, and 1% remain unclassified unknown [137]. The Directive evaluates forest condition based on the presence and abundance of key species from different taxonomic groups. Since the monitored habitats represent only 28% of the EU forest area, the condition of the remaining 72% is largely unknown and may also be unfavourable [127]. Therefore, further monitoring and restoration efforts need to be considered. Forest management practices should ensure good habitat conditions beside good biomass growth. Since plants are the first in the food chain, enhancing plant diversity will promote better habitat conditions. This can be done through afforestation and cultivation of autochthonous species and integration of pollinators.

### 6.3.2 *Loss of genetic diversity*

Genetic diversity of forests is essential for its conservation, and it is highly impacted by management practices. Forest management practices such as selective harvesting and clear-cutting, followed by either natural or artificial regeneration, can alter population structure and reproductive dynamics, influencing gene flow and overall genetic diversity. These changes may negatively affect the survival and productivity of both tree and understory species, with potential consequences for the wider ecosystem. The magnitude of these genetic and ecological effects largely depends on the management strategy used, the characteristics of the ecosystem, and the species involved. For instances, Table 1 report overall genetic impact observed on species grown under different management conditions. Nonetheless, proper management practices should consider site-specific conditions such as the population size and density, reproductive biology and growth rate of a species, to ensure that genetic diversity and habitat are maintained [138].

Table 1. Impact of different management practices in forest genetic diversity [138].

| Impact on genetic diversity | Management practices | Tested species |
|---|---|---|
| Not affected | Artificial and natural regeneration | *Picea mariana* |
| | Clear-cut harvesting | *Picea sp. And Pseudotsuga menzeisii* |
| | | *Eucalyptus sieberi and Eucalyptus consideniana* |
| | Coppice | *Castanea sativa* |
| | Green tree retention | *Picea glauca and Tsuga heterophylla* |
| | Group selection | *Pseudotsuga menzeisii* |
| | | *Pinus sylvestris* |
| | Patch cut | *Tsuga heterophylla and Abies amabilis* |
| | Shelterwood | *Pseudotsuga menzeisii and Tsuga heterophylla* |
| | | *Pinus sylvestris* |
| Specie dependent | Selective logging | *Shorea sp., Scaphium macropodum, Parkia speciosa, Daemonorops verticillaris, Garcinia malaccensis, Calophyllum ferrugineum* var. *oblongifolium, Labisia pumila, Tectaria singaporeana, Dicorynia guianensis, Sextonia rubra, Symphonia globulifera, Voucapua, Carapa sp. americana* |
| Negative impact | Tree improvement | *Picea glauca* |
| | Seed tree retention | *Pinus strobus* |
| | | *Eucalyptus sieberi and Eucalyptus consideniana* |
| | Selection cut | *Tsuga canadensis* |
| | Pine release | *Pinus strobus* |
| | Diameter limit cuts | *Tsuga canadensis* |
| | Fragmentation | *Quercus ilex* |
| | | *Taxus baccata* |
| | | *Swietenia humilis* |
| | | Review of 23 neotropical species |
| | Commercial thinning | *Pseudotsuga menzeisii, Tsuga heterophylla, Thuja plicata, Pinus monticola, Abies amabilis* |

## 6.4 Social impact

Biomass has historically played a central role in human energy use and continues to be a significant component of today's energy mix. In many regions, especially rural areas with limited access to centralized energy infrastructure, decentralized bioenergy production provides an important pathway to modern, affordable, and cleaner energy services, reducing dependence on fossil fuels and supporting a transition toward a bio-based economy. Biomass systems can also support rural development by creating local supply chains, co-products and offering new revenue streams for farmers and foresters. On the other hand, air pollution and visual impact of degraded habitats create strong social rejection, these impacts need to be addressed [123].

### 6.4.1 *Renewable and non-intermittent production*

In 2022, the global installed capacity for renewable electricity reached approximately 3,381 GW. Hydropower remained the dominant technology, accounting for about 1,393 GW of installed capacity, followed by solar energy with around 1,062 GWp worldwide. In comparison, bioenergy-based electricity generation represented

151 GW. Although bioelectricity capacity is considerably lower than that of hydropower and solar, it offers the advantage of continuous, non-intermittent power generation and generally achieves higher capacity factors. In addition, biomass is used primarily for heat production rather than electricity generation, with heating applications representing roughly 88% of total bioenergy use. This indicates a significant potential for further development of biomass-based electricity production [136].

### 6.4.2 *Rural deployment and local chains*

The bioenergy sector generates employment mainly through the construction of facilities and the manufacture of equipment required for new installations, while the operation and maintenance of bioenergy plants create longer-term jobs. In contrast to other renewable energy technologies such as solar, wind, geothermal, or hydropower, bioenergy systems also require continuous activities related to biomass collection, processing, and transportation before final use. These additional supply chain activities can support stable employment opportunities and contribute to economic development in rural areas [136].

# 7. HYDROPOWER IMPACT IN AGRICULTURE

Hydropower is a key renewable energy source, accounting the 41% (1,393 GW) of the global installed capacity for renewable electricity in 2022, but this is due to the capacity of big scale dams (up to 200 GW/h). On-farm facilities are small scale hydropower generators (up to 2 MW/h), also referred to as micro-hydro systems, that consists of pressurized irrigation systems connected to agricultural dams or natural aquatic ecosystems. While big scale dams can create significant ecological pressures, micro-hydropower systems have minimal impacts if water reservoirs are already available. This section reviews the current state-of-art of micro-hydro systems and its potential impact on farms.

## 7.1 Micro-PHES systems

The use of flowing water to provide mechanical power has a long history in agricultural and industrial activities; for instance, traditional flour mills used waterwheels driven by streams to operate grinding equipment. Modern technologies, such as micro-hydro systems, make it possible to capture the energy of moving water not only for mechanical applications (irrigation) but also for electricity generation [139].

Micro-pumped hydro-energy storage (micro-PHES) is an emerging technology that utilizes existing farm dams for sustainable power management. The system operates by pumping water from a lower reservoir to an upper one (**¡Error! No se encuentra el origen de la referencia.**A and B) during periods of surplus electricity generation, such as from solar or wind sources [140]. This upward transfer stores energy as gravitational potential energy, this potential energy can be captured between a dam and a river, or between two dams. When energy demand increases or solar production ceases, the stored water is released downward through a turbine to produce electricity (**¡Error! No se encuentra el origen de la referencia.**C). Integrating micro-PHES with solar photovoltaic (PV) installations enables the capture and use of excess solar energy.

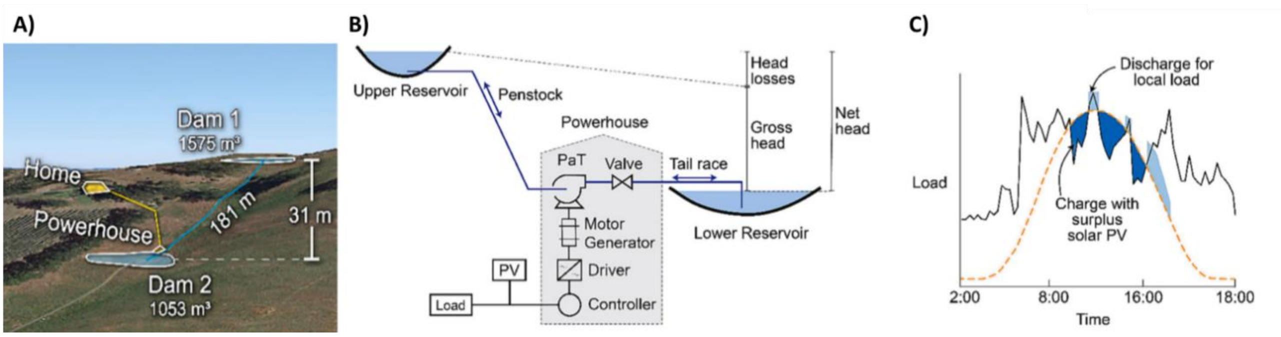


Figure 10. A) Concept design of a micro-PHES. B) Hardware configuration for micro-PHES. C) Example charge-discharge operation for micro-PHES, noting that solar generation capacity (kW), storage capacity (kW, kWh) and load will alter the charge and discharge profiles. Images obtained from [141].

Besides pipes and the water reservoirs, installing micro-hydro systems take little extra surface, this is a powerhouse of about 6 $m^2$. Most farms do not need to install new pipes nor obtain a new legal water right if there is an existing water use, this can be farm dams and rivers. Current EU strategies focus on increasing power output while avoiding new environmental disturbances, in this sense, it is highly unrecommended to construct new water reservoirs due to their great impact on the ecosystem's hydrology, but also it is too expensive [141]. Therefore, here is assumed that no new water reservoirs need to be built, otherwise micro-hydro systems are not profitable for a farmer. Besides, an overview of the impacts of farm dams is provided in following sections.

### 7.1.1 *Benefits of micro-PHES systems in farms*

Pilot projects of micro-PHES systems in farms (applied with existing water reservoirs) suggest that the technology's capacity for long-duration energy storage can contribute to lowering energy expenses and reducing carbon emissions, while enhancing overall energy reliability [141]. Compared with battery systems, micro-hydro pumps demonstrate greater storage capacity, longer operational lifespan, and lower environmental impacts across categories such as global warming potential, resource depletion, eutrophication, and human health. Furthermore, repurposing existing farm dams minimizes land use changes typically associated with large-scale energy developments [142].

Moreover, micro-hydro systems allow to obtain energy making a better use of water, reducing dependency on fossil fuels to power irrigation. For instances, a pilot plant substituted the use of diesel for irrigation by a micro-hydro system and estimated an annual saving of approximately 2950€ and 11 t $eCO_2$ [143]. The versatility of micro-hydro systems allows their integration into a wide range of existing hydraulic infrastructures, including water distribution systems, wastewater treatment facilities, non-powered dams, and restored historic watermills, allowing the recovery of unused energy resources while maintaining a relatively low environmental impact [144].

### 7.1.2 *Counterparts of micro-PHES systems in farms*

While large-PHES systems and large dams are well-established technologies, integration of micro-PHES systems in farms are still under deployment and offer considerable potential for further efficiency improvements. One promising approach is the use of pumps operating as turbines, which is particularly suitable for small-scale PHES applications and is currently the focus of ongoing research aimed at improving performance in both pumping and generating modes. However, there is still a lack of real-world operational data, as most existing studies are limited to pilot installations, often located on university campuses. In addition, regarding the creation of water reservoirs, micro-PHES systems can lead to greater land transformation impacts than many other renewable energy sources, while also contributing to visual disturbance and noise pollution [141].

## 7.2 Agronomic impacts of farm dams

Regarding the impacts of farm dams, specifically, these dams have no negative impacts for the crop, in fact, it might be a need when they are constructed for irrigation requirements. However, its environmental impact can be so high that long term effects might affect to the agricultural system, by altering the hydrology of the ecosystem for years. Therefore, to set a cropping system, it is important to consider the water availability and to use crops well adapted to the environmental conditions.

## 7.3 Environmental impacts of farm dams

Small farm dams can generate significant hydrological and environmental impacts, particularly when they are numerous within the same river basin. These reservoirs reduce river discharge because water captured during the wet season is later used for irrigation and therefore does not return to the river system [145].Consequently, they can decrease annual river flows by up to 20% and even more than 50% in dry years. The impacts are especially pronounced during the filling period, when dams intercept runoff and small stream flows, leading to substantial decreases in monthly high and low flows. Furthermore, climate change is expected to aggravate these impacts by reducing the efficiency of dam filling and increasing water scarcity, making farm dams less reliable for irrigation supply while further stressing river ecosystems [145]. New strategies to increase water-use efficiency are essential, technologies such as micro-hydro systems, that provides energy while irrigation, need to be further developed.

## 7.4 Biodiversity impacts of farm dams

Water capturing by farm dams produces substantial decreases in river flows, that may negatively affect ecological processes such as fish migration and river morphology, affecting the river's ecosystem and arounds [145]. In the case of extracting only energy, a micro-hydro system could be installed in a recirculation system that returns water to the river; hence no dam is needed, reducing draught impact to the minimum. However, ownership of river-river hydropower systems might be public and not integrated in a farm.

## 7.5 Social impacts of farm dams

Disturbance of the landscape is the major social impact of farm dams. The aesthetic of dams is not highly appreciated but its impact had never been very remarkable.

# 8. HYBRID-RES SYSTEMS

Currently, the EU strategies focus on increasing power output while avoiding new environmental disturbances. For example, modern hydropower operations can offer important benefits, such as supporting water management, providing system flexibility, and enabling higher shares of variable renewables like wind and solar. Central to this approach is the modernisation of Europe's ageing hydropower fleet, which can improve efficiency and flexibility without altering natural river systems.

Hybrid systems such as floating solar PV on hydropower reservoirs allows additional renewable generation without occupying new land or creating new barriers. However, careful planning is needed to ensure that these advantages do not come at the expense of the ecosystem [144]. In this sense, hybrid-RES systems are especially profitable for off-grid farms because they can assure an energy supply independently of the weather [146]. This is because the robustness of hybrid systems allows to allocate them in farms where the climatic conditions are not necessarily appropriate for a concrete RES. Therefore, the applicability of hybrid-RES systems is wider and more efficient than one-RES systems [147] (**¡Error! No se encuentra el origen de la referencia.**). Nonetheless, installation, management and accessibility to qualified support became more demandant than one-RES system, limiting its deployment in farms. Currently, the most widespread hybrid system is the PV-wind system [146].


Figure 11. Examples of hybrid-RES systems integrated in farms (own source)

Regarding the impact of hybrid systems, it is expected to be increased, as its agronomic-environmental impact is generally similar than each RES independently. However, mitigation measures exposed in this delivery can apply equally to hybrid systems. The type of farm and its management may be considered when integrating different RES to enhance farm efficiency and sustainability, accordingly, different hybrid-RES systems are recommended (Table 2). The efficiency of hybrid systems combined with appropriate land management can lever up the agriculture-energy dual benefit in farms while mitigate climate change.

Table 2. General recommendations of hybrid-RES systems according to the type of farm.

| Type of farm | Recommended hybrid-RES systems |
|---|---|
| Animal farm | Biogas + Solar energy + Wind energy |
| Dryland cropping | Agri-voltaic + Micro-hydro power (supported by solar energy) + Wind energy |
| Irrigated cropping | Agri-voltaic + Micro-hydro power (supported by solar energy) |
| Tree cropping | Bioenergy + Micro-hydro power (supported by solar energy) |

# 9. SUMMARY OF MITIGATION STRATEGIES

## 9.1 Criteria for the selection of appropriate mitigation measures

The selection of **mitigation measures** was guided by a set of clearly defined criteria to ensure their relevance, feasibility, and effectiveness within agricultural contexts. The proposed measures were required to be technically feasible, compatible with existing farming practices, and adaptable to different territorial and regulatory contexts across Europe. The identification and validation of mitigation options were based on multiple **information sources, including peer-reviewed scientific literature, technical guidelines and standards, results from previous European and national research projects, and evidence collected from the initiatives and case studies mapped within the HarvRESt projec**t. Scientific robustness was ensured by favouring measures supported by empirical evidence or documented best practices. In addition, the selection process considered the capacity of each measure to be monitored and evaluated through available or proposed key performance indicators (KPIs), enabling quantitative assessment of their effectiveness over time.

## 9.2 Consolidated tables of impacts and mitigation measures

Mitigation measures are proposed to specific negative impacts related to the integration of each RES in a farm. KPIs identified in Deliverable 2.2 of HarvRESt project are added as suggested methods for performance-quantification, whereas KPIs identified in Deliverable 4.2 assess agronomical and environmental impacts with critical thresholds for impact-quantification (Table 3). Positive impacts from the integration of each RES in farms are collected in Table 4.

Table 3. Negative impacts from each RES, mitigation measures and KPIs.

| NEGATIVE IMPACTS | MITIGATION MEASURES | RELATED KPI | |
|---|---|---|---|
| | | From D4.2 (Agro. & Env. impact) | From D2.2 (General performance) |
| SOLAR | | | |
| Reduced solar radiation (PAR) affecting crop growth and yield | Optimized PV infrastructure design (panel height, spacing, tilt, module type, dynamic tracking systems) | KPI.AG.01.03 Reduction of solar radiation and leaf area index | KPI.EV.08 Reduction of Solar Radiation received by the crop |
| | Selection of suitable (shade tolerant) crops | | KPI.EN.14 PV Performance in an Agrivoltaic System |
| Altered air/soil temperature and humidity (VPD) affecting plant function and stress | Strategic crop selection for thermal benefits | KPI.AG.01.03 Reduction of solar radiation and leaf area index | KPI.EV.07 Reduction of soil and air temperature |
| Changes in soil moisture and evapotranspiration rates leading to water stress or reduced irrigation needs | Leveraging shading for reduced evapotranspiration and enhanced water saving | KPI.EV.01.05 Soil water-holding capacity (WHC) and water content | KPI.EV.06 Changes in the crop micro-climate (ETo reduction) |
| | Strategic irrigation management (e.g., drip irrigation, precision agriculture) | | KPI.AG.07 Irrigation Water Consumption |
| Rainfall redistribution and localized water availability | Advanced panel designs and management to ensure uniform water distribution | | KPI.AG.07 Irrigation Water Consumption |
| Wind speed and direction affecting plant function and stress | Optimized PV infrastructure design (panel height, spacing, tilt, module type, dynamic tracking systems) | Crop Health (KPI.AG.01.0.1-0.3) | KPI.EV.06 Changes in the crop micro-climate (ETo reduction) |
| Soil compaction | Low-impact construction and maintenance practices | Soil Quality Impact (KPI.EV.01.01-05) | KPI.EV.01 Soil Quality Impact |

| | | | |
|---|---|---|---|
| Altered soil organic fractions | Soil management technics such as composting | KPI.AG.03.01 Soil organic matter (SOM) and carbon (SOC) | KPI.EV.01 Soil Quality Impact |
| Nutrient imbalance and depletion | Co-location in degraded/low-productive environments | Soil C and Nutrient Status (KPI.AG.03.01-05) and Nutrient Use Efficiency (KPI.AG.02.01-0.3) | KPI.EV.04 N & P Losses |
| Soil erosion due to runoff | Strategic vegetation and land management | Soil Quality Impact (KPI.EV.01.01-05) | KPI.EV.01 Soil Quality Impact |
| | Application of drainage systems or enhancement of soil-infiltration capacity | | KPI.AG.07 Irrigation Water Consumption |
| Heterogeneous microbial activity | Leveraging shading for more homogeneous moisture and light conditions | KPI.EV.01.04 Soil biological activity | KPI.EV.01 Soil Quality Impact |
| Increased humidity leading to diseases | Optimized water management | KPI.EV.01.05 Soil water-holding capacity (WHC) and water content | KPI.AG.07 Irrigation Water Consumption |
| Habitat degradation and ecological traps | Strategic siting and design to avoid sensitive habitats | KPI.EV.02.01 Vegetation diversity and cover and KPI.EV.02.02 Weed-insect pollinator indicator | NA |
| | Co-location with compatible livestock grazing | | NA |
| Shift in plant and insect communities | Integration of pollinator-friendly vegetation and habitat creation through enhancement of plant diversity | | NA |
| Perception of land competition (PV vs. Food crops) | Outreach actions to show that agrivoltaics are complementary with agriculture rather than competitive | NA | KPI.SC.07 Public Engagement |

| BIOGAS | | | |
|---|---|---|---|
| High ammonium content (↑ $NH_4^+$, high mineral N) and ammonia volatilization ($NH_3$) | Acidification (shift $NH_3 \rightarrow NH_4^+$); injection/trailing-shoe; apply under cool, moist, low-wind conditions; rapid incorporation; covered storage; membrane concentration or stripping to create stable mineral-N fertilisers. | KPI.AG.03.02 Total N | KPI.EV.02 Reduction in GHG Emissions |
| Phosphorus runoff & eutrophication | P-based application, solid–liquid separation, export of solid fraction, struvite/Ca-P precipitation, field P mapping + deficit-area redistribution. | KPI.AG.03.04 Available P | KPI.EV.04 N & P Losses |
| High potassium availability | None; optimise via fertigation of LF. | KPI.AG.03.05 Available K | KPI.EV.01 Soil Quality Impact |
| Low C:N ratio | Not required, except when blending with high-C residues for soil conditioning. | Soil C and Nutrient Status (KPI.AG.03.01-05) | KPI.AG.03 Soil C and Nutrient Status |
| Soil acidification / alkalinisation | pH monitoring; tailored liming; acidification strategies; avoid overdosing. | KPI.EV.01.02 Soil pH | KPI.AG.04 Soil Acidity |
| Organic matter contribution (moderately stabilised) | Combine liquid-fraction fertilisation with composted solid fraction to improve SOM build-up. | KPI.AG.03.01 Soil organic matter (SOM) and carbon (SOC) | KPI.EV.01 Soil Quality Impact |
| Risk of phytotoxicity / insufficient stabilisation | Composting of SF; post-aeration; blending; curing; avoid use on seedlings. | Soil Quality Impact (KPI.EV.01.01-05) | KPI.EV.01 Soil Quality Impact |
| Variability of composition and lack of standardisation | Digestate profiling; standardised sampling; processing to create homogeneous end-products (pellets, ammonium sulphate, RO concentrates). | Soil C and Nutrient Status (KPI.AG.03.01-05) | KPI.EV.01 Soil Quality Impact |

| | | | |
|---|---|---|---|
| Nitrate leaching ($NO_3^-$) | Avoid autumn applications; split doses; nitrification inhibitors; LF concentration; export of N via AS/AN products. | KPI.AG.03.03 Nitrates | KPI.EV.04 N & P Losses |
| Greenhouse gas emissions ($CH_4$, $N_2O$) | Covered storage; acidification; injection; controlled aeration; composting with forced aeration; avoidance of VFAs in digestate. | KPI.EV.02.03 Soil emissions | KPI.EV.02 Reduction in GHG Emissions |
| Heavy metal dispersion | Feedstock control; avoid sludge; export of SF; biochar/HTC immobilisation; strict monitoring. | KPI.EV.02.04 Heavy metal pollution | NA |
| Microplastic accumulation | Source separation; depackaging; fine screens; avoid contaminated OFMSW; only accept high-quality inputs. | KPI.EV.02.06 Microplastic contamination | NA |
| Pathogen survival & regrowth | Thermophilic AD; hygienisation (70°C–1h); composting; lime; thermal drying; injection to reduce crop contact. | KPI.EV.02.05 Pathogen contamination | NA |
| Salinity / electrical conductivity increase | Dilution; mix with low-salt materials; apply SF instead of LF; blending with freshwater irrigation. | KPI.EV.01.03 Electric conductivity (EC) | KPI.EV.01 Soil Quality Impact |
| Water use & concentrate disposal (membrane systems) | Integrate RO/ED with fertiliser manufacturing; evaporative concentration; nutrient crystallisation (struvite, Ca-P). | NA | KPI.EC.11 Levelized Cost of Storage (LCOS) |
| Energy consumption & carbon footprint of advanced treatments | Use waste heat; integrate CHP; renewable electricity; LCA-based selection; optimise separation before membranes. | NA | KPI.EC.10 Investment ROI |
| Potential land competition (Energy crops vs. Food crops) | Use energy cover crops instead, a combination of energy and food crops that avoid land competition | NA | KPI.EC.01 Profit per Hectare |

| | | | |
|---|---|---|---|
| Operational breakdowns and mismanagement due to lack of qualified support | Investing in AD with subsidies and supportive policies would increase the market and the accessibility to qualified support | NA | KPI.SC.06 RES-enabled Farming Engagement |
| WIND | | | |
| Wake effect and air turbulences | Selection of adequate crops to resist wind while its roughness is favourable for energy harvesting | Crop Health (KPI.AG.01.0.1-0.3) | KPI.EV.06 Changes in the crop micro-climate (ETo reduction) |
| | Optimized blades design | | |
| Soil evapotranspiration | Strategic irrigation management (e.g., drip irrigation, precision agriculture) | KPI.EV.01.05 Soil water-holding capacity (WHC) and water content | |
| Nocturnal temperature inversions | Switching off-on wind turbines to reduce day-night effects | | KPI.EV.07 Reduction of soil and air temperature |
| Shaded areas and flickering | Optimized wind turbine design | KPI.AG.01.03 Reduction of solar radiation and leaf area index | KPI.EV.08 Reduction of Solar Radiation received by the crop |
| | Switching wind turbines accordingly to light-day | | |
| Forest fragmentation and soil degradation during construction | Low-impact construction and maintenance practices | Soil Quality Impact (KPI.EV.01.01-05), KPI.EV.02.01 Vegetation diversity and cover and KPI.EV.02.02 Weed-insect pollinator indicator | KPI.EV.01 Soil Quality Impact |
| Reduced invertebrate communities due to soil compaction and vibration | Low-impact construction and maintenance practices | | |
| | Optimized basement design of wind turbine | | |
| Noise | Optimized blades design | NA | KPI.SC.01 Social Acceptability |
| Visual impact on landscape | Preventive tools for wind farm design | | |

| | | | |
|---|---|---|---|
| BIOENERGY (from thermochemical processing) | | | |
| Biomass mismanagement - carbon imbalance, GHG emissions | Monitor biomass growth, carbon uptake and carbon balance of the entire energy production system, reduce transport distances and optimize conversion processes | Crop Health (KPI.AG.01.0.1-0.3) | KPI.EC.01 Profit per Hectare and KPI.EV.02 Reduction in GHG Emissions |
| Soil erosion and nutrient depletion | Avoid excessive harvesting, ensure nutrient and water supply according to the sustainable ecosystem requirements, as well as sustainable management practices | Soil C and Nutrient Status (KPI.AG.03.01-05) and Soil Quality Impact (KPI.EV.01.01-05) | KPI.EV.01 Soil Quality Impact and KPI.AG.03 Soil C and Nutrient Status |
| Land and feedstock competition | Prioritize the use of residues and better management practices, such as complex agro-forest systems | NA | |
| Forest exploitation | Prioritize the use of residues and better management practices. To extend woodlands, plantations should match soils with nutrient-excess to restore them, and other practices such as afforestation and forest restoration. | NA | KPI.SC.06 RES-enabled Farming Engagement |
| Air pollution | Optimize processes to avoid pollutant dispersion | NA | KPI.EV.02 Reduction in GHG Emissions |
| Energy consumption & carbon footprint of pre-treatments and energy carriers | Optimize processes, reduce transport distances and prioritize local chains | NA | KPI.EC.10 Investment ROI |

| | | | |
|---|---|---|---|
| Habitat degradation and lose of biodiversity | Management practices that consider site-specific conditions to ensure habitat conditions besides biomass growth | KPI.EV.02.01 Vegetation diversity and cover and KPI.EV.02.02 Weed-insect pollinator indicator | NA |
| | Strategic siting and design to avoid sensitive habitats | | |
| | Co-location with compatible livestock grazing | | |
| | Integration of pollinator-friendly vegetation and habitat creation through enhancement of plant diversity | | |
| Visual impact on landscape | Prioritize the use of residues rather than grown trees, and better management practices | NA | KPI.SC.06 RES-enabled Farming Engagement |
| FARM DAMS | | | |
| River drainage | Enhance water-use efficiency while reducing water requirements to the minimum | KPI.EV.01.05 Soil water-holding capacity (WHC) and water content | KPI.AG.07 Irrigation Water Consumption |
| Habitat degradation in river ecosystems | | | |
| Water loses through evaporation | Cover dam, reduce surface-use increasing dam deep | | KPI.EC.11 Levelized Cost of Storage (LCOS) |
| Impact on landscape | Minimize land use and dig pipes | NA | KPI.SC.01 Social Acceptability |

Table 4. Positive impacts of integrating each RES in farms.

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|---|
| SOLAR |
| Improves water-use efficiency and soil moisture retention; reduces heat stress and evapotranspiration; enhances crop resilience to drought and heatwaves; can maintain or improve yields in shade-tolerant crops; protects crops from extreme weather events; enables dual land use for food and energy production. |
| Reduces erosion when vegetation cover is maintained; supports rainwater harvesting; may improve degraded soils under proper management; lowers GHG emissions compared with fossil-fuel energy systems; improves microclimatic regulation. |
| Can create pollinator-friendly habitats; promotes native vegetation under ecological management; reduces land conversion pressure by combining agriculture and energy generation; provides shelter for livestock and associated fauna. |
| Diversifies farmer income through electricity generation; improves farm resilience and energy autonomy; maintains agricultural activity while producing renewable energy; supports rural employment and local acceptance when integrated with farming; contributes positively to multiple Sustainable Development Goals. |
| BIOGAS |
| Produces digestate as an organic fertiliser rich in plant-available nutrients; improves nutrient recycling; supports circular agriculture; enhances soil fertility and nutrient-use efficiency; enables co-digestion synergies between wastes and agricultural residues. |
| Reduces methane emissions from unmanaged manure and organic wastes; valorises agricultural and municipal residues; lowers dependence on mineral fertilisers; supports nutrient recovery technologies; reduces landfill disposal and associated emissions. |
| Lower biological pressure due to manure treatment; can support more stable soil microbial activity when digestate is properly managed; reduces uncontrolled waste accumulation. |
| Creates rural jobs and technical employment; promotes local energy production and energy independence; supports territorial synergies between farms, industries and municipalities; strengthens circular economy approaches. |
| WIND |
| Minimal occupation of agricultural land, allowing continued farming activities; low water consumption compared with conventional power plants; can slightly moderate microclimatic conditions. |
| Produces renewable electricity with low operational emissions; requires relatively small permanent land footprint; contributes to climate-change mitigation. |

| |
|---|
| Agricultural land around turbines may remain available for vegetation and some wildlife habitats if properly managed. |
| Provides additional income to landowners through land leasing; supports rural development and energy diversification; contributes to local renewable-energy supply. |
| BIOENERGY (from thermochemical processes) |
| Revalorises agroforestry residues and biomass streams; may contribute to nutrient and carbon recycling through biochar application; supports biomass management. |
| Provides stable and non-intermittent renewable energy; supports carbon sequestration potential; reduces wildfire risk through biomass removal; promotes residue valorisation and reduced waste accumulation. |
| Can support landscape management and fuel-load reduction when sustainably managed. |
| Strengthens local biomass value chains; promotes rural deployment and local employment; contributes to energy security through dispatchable renewable energy generation. |
| Micro-PHES systems |
| Supports on-farm energy storage and management; can integrate with irrigation infrastructure and farm dams. |
| Provides low-emission renewable electricity and energy-storage capacity; existing farm dams minimise additional land disturbance. |
| Very limited biodiversity impacts when based on pre-existing farm dams and small-scale systems. |
| Enhances farm energy autonomy and resilience; supports flexible energy management in farms; low operational impacts when existing infrastructure is used. |

## 9.3 Monitoring and verification methods

The effective deployment of renewable energy systems in agricultural landscapes requires robust, transparent and practical monitoring and verification methods capable of capturing the full range of agronomic, environmental, soil-related, biodiversity and social impacts described in this deliverable. These methods must be applicable across the main renewable energy systems considered, including solar PV, agrivoltaics, wind energy, hydropower, biomass and anaerobic digestion, as well as hybrid systems.

Agronomic monitoring focuses on variables such as microclimate, crop growth, yield, soil moisture and nutrient dynamics, enabling the detection of changes induced by shading structures, airflow modifications or the application of digestate as fertiliser or organic amendment. Environmental and soil monitoring includes the assessment of soil structure, erosion risk, organic matter dynamics, biological activity, infiltration capacity and overall soil health. Biodiversity monitoring encompasses vegetation composition, ground cover, pollinator presence, soil fauna communities and habitat quality indicators within and around renewable infrastructures.

Social monitoring examines elements such as public acceptance, perceived benefits and risks, landscape integration, operational compatibility with farming activities and the distribution of costs and benefits among stakeholders.

A central principle of this framework is the selection of indicators that are scientifically meaningful yet sufficiently simple, accessible and cost-effective so that farmers and land managers can measure them directly. Indicators that require specialised equipment or complex laboratory procedures limit long-term continuity and reduce farmers' ability to understand and manage impacts. Therefore, priority is given to metrics that can be monitored using basic tools, low-cost sensors, visual assessments supported by clear protocols or existing open-access data sources. This approach ensures that monitoring can be integrated into routine agricultural practices and contributes to a shared understanding of system performance. Remote sensing, digital platforms and sensor networks can complement this approach by providing consistent, large-scale and high-frequency information on vegetation development, land surface temperature, soil moisture and landscape structure. These tools are increasingly accessible and can be interpreted through user-friendly interfaces, making them a practical and easy-to-follow source of information for farmers and land managers. When combined with simple in-field observations or visual assessments, they strengthen verification and help capture both immediate and long-term effects of renewable energy deployment in agricultural settings.

Ultimately, the purpose of this monitoring framework is to ensure that the selected indicators allow stakeholders to track, quantify and interpret the agronomic, environmental, soil, biodiversity and social impacts outlined throughout this Deliverable. By linking monitoring results to real system responses, this approach supports adaptive management and provides a coherent basis for developing effective mitigation strategies in the following sections. To complement this monitoring framework, Table 3 summarises the main impact categories identified in this report, alongside indicative indicators and the corresponding monitoring approaches. This allows specific indicators to be considered for monitoring the aforementioned impacts of each RES throughout the deliverable.

## 9.4 Cooperation between farmers and stakeholders

The integration of renewable energy systems into agricultural landscapes often involves multiple actors with different roles, responsibilities and interests. As highlighted in the previous section, effective monitoring of agronomic, environmental, soil, biodiversity and social impacts depend not only on the availability of suitable indicators but also on the willingness and capacity of stakeholders to share information, coordinate actions and ensure continuity in data collection. For this reason, cooperation is not merely desirable: it is an essential condition for implementing meaningful monitoring and for enabling adaptive management throughout the lifetime of renewable energy installations.

The effective deployment of renewable energy systems in agricultural areas therefore relies as much on collaborative processes as on technical and environmental performance. Farmers, landowners, developers, technology providers, public authorities and local communities all play a role in shaping how renewable infrastructures operate and interact with agricultural systems. Their involvement is critical to ensuring that renewable energy projects contribute to sustainable rural development while minimising disruptions to farming activities.

Farmers are central to this cooperation framework. Their practical knowledge of field operations, soil conditions, crop cycles and livestock systems provides essential insights into how renewable technologies can be integrated without compromising agricultural viability. Early and continuous engagement allows operational needs, such as machinery access, soil protection measures, grazing patterns, digestate application schedules or shading implications, to be anticipated and incorporated into project design. When developers work transparently with farmers, it becomes possible to jointly identify design and management options that adapt renewable energy infrastructures to the specific conditions of each agricultural context. This collaborative approach supports the development of solutions that minimise operational constraints, respect local agronomic practices and enhance compatibility between energy generation and agricultural production.

Constructive cooperation also requires clear governance mechanisms and fair benefit-sharing arrangements. Well-defined contractual frameworks, long-term stewardship agreements and transparent communication channels help align expectations and ensure that both risks and benefits are equitably distributed. Local and regional authorities play a pivotal role in facilitating dialogue, mediating interests when necessary and ensuring that renewable projects are coherent with land-use planning, environmental regulations and agricultural policy objectives.

Enhanced cooperation also strengthens social acceptance. Rural communities are more likely to support renewable energy development when they perceive tangible benefits, such as increased biodiversity, improved land management, diversification of farm income, reduced reliance on fossil fuels or reinvestment in local services. Participatory processes, open communication and ongoing consultation can help address concerns related to landscape integration, land availability and perceived disruptions to agricultural activities.

In summary, cooperation between farmers and stakeholders is a cornerstone of sustainable renewable energy deployment in agricultural landscapes. It ensures that agronomic, environmental and social considerations are integrated into project design and operation, supports the effectiveness of mitigation measures, and provides a foundation for the policy and regulatory considerations addressed in the following section.

## 9.5 Examples of HarvREST use-cases

Use-cases are pilot demonstrations based on real data collected experimentally or from relevant data bases. The HarvREST use-cases include from real farms to digital tools for decision support, and they apply a wide range of RES in farm systems with sustainable agronomic practices. Note that use-cases were not originally designed around the mitigation measures and KPIs developed in this work, in fact, preliminary identification of KPIs was possible thanks to these use-cases and, together with the present mitigation measures catalogue, subsequent refining of KPIs to monitor impacts is feasible. Herein, integration of mitigation measures and KPIs identified in HarvREST use-cases are shown as examples of their application into reality.

### 9.5.1 *Torre Santamaría farm with biogas integration*

The Torre Santa María farm is a use-case in Catalunya (Spain) that brings together a valuable collaboration between the BETA Technological Center and the business group Sorigué, together with Axpo and the farm itself, under the partnership known as Noguera Renovables. Torre Santa María is a dairy farm that integrated a biogas plant with four digesters, to optimize energy production from treating agricultural residues while enhancing the circularity of the farm through digestate valorisation. To this aim, the fertilizer potential of digestate was evaluated in a 3-hectare irrigated field that is located adjacent to the farm.

This use case used the following key performance indicators (KPIs) to evaluate the impact of digestate, while applying different **mitigation measures**:

- KPI.AG.03.01 Soil organic matter and carbon | KPI.AG.03.04 Available P | KPI.AG.03.05 Available K — **Solid–liquid separation** is applied as a core management strategy, allowing the solid fraction (SF) and liquid fraction (LF) to be applied separately and at different times of the year according to crop nutrient demand. This reduces the risk of phosphorus accumulation and allows more precise nutrient management. The SF is **composted with organic matter inputs and forced aeration** prior to application, and part of it is exported or commercialised, contributing to nutrient redistribution beyond the farm. No critical potassium excess was identified, and distribution was managed through the coordinated application of LF and SF. The application of composted SF furthermore contributed to enhancing long-term soil organic matter build-up.

- KPI.AG.03.02 Total N | KPI.AG.02.01 Fertilizer N-use efficiency | KPI.EV.02.02 Farm GHG emissions — High ammonium content was detected in digestate, which can lead to ammonia volatilization and N losses not taken up by biomass. To reduce field-level emissions, **LF application is avoided during autumn,** and the **SF is rapidly incorporated into the soil** after spreading. Greenhouse gas emissions from **storage lagoons will be partially mitigated once it is covered**.
- KPI.AG.03.03 Nitrates | KPI.AG.02.02 Fertilizer P-use efficiency — Nitrate leaching risk was monitored throughout the trial. The **avoidance of LF applications in autumn** and the use of **temporally split applications** between SF and LF were the main strategies adopted to minimise N losses to groundwater. Additionally, pilot-scale trials are ongoing to evaluate **struvite and ammonium salt precipitation** as advanced P and N recovery pathways, though these are not yet implemented at plant level.
- KPI.EV.01.01 Soil texture | KPI.EV.01.02 Soil pH | KPI.EV.01.03 Electric conductivity — Soil physical and chemical baseline conditions were characterised through texture, pH and electrical conductivity measurements, no mitigation measures were required to correct soil condition. These parameters were tracked through **periodic monitoring of both input digestate fractions and soil outputs**, enabling early detection of any adverse trends in soil quality.
- KPI.EV.02.03 Heavy metal pollution — Heavy metal content was screened in both digestate fractions and amended soils. Mitigation relied on **strict and systematic monitoring of input feedstocks** to ensure compliance with quality thresholds before application.
- KPI.AG.01.01 Critical plant density | KPI.AG.01.02 Critical biomass density — Crop response to digestate fertilisation was assessed through plant density and above-ground biomass production, providing integrated indicators of agronomic performance under the different treatment conditions.

### 9.5.2 *Viñedos del Río Tajo, a vineyard with agrivoltaics*

Viñedos del Río Tajo is a use-case in Castilla la Mancha (Spain) that brings together a valuable collaboration with CIRCE (Research Centre of Resources and Energy Consumption). This use-case integrates agrivoltaics within vineyards. They have a pilot 50 kW PV installation in Daramezas vineyard, close to the city of Toledo, where the interaction of solar panels with the vines physiology and performance is studied.

This use case used the following key performance indicators to evaluate the impact of photovoltaic panels on vineyard while applying different **mitigation measures**:

- KPI.AG.03.01 Soil organic matter and carbon | KPI.AG.03.04 Available P | KPI.AG.03.05 Available K | KPI.AG.03.02 Total N | KPI.AG.02.01 Fertilizer N-use efficiency — The same fertilization is being applied in both shaded areas and non-shaded areas to compare them. Soil analysis will allow to compare the available organic matter, N, P and K in each case. **Monitoring soil quality and adjusting fertilization** to soil requirements will reduce the amount of fertilizer and the loss of nutrients.

- KPI.EV.01.05 Soil water-holding capacity (WHC) and water content — Water content in shaded areas was compared to non-shaded areas (both irrigated with the same amount of water), showing an increment of 14% in shaded areas in 2024 and 17% in 2025. This allowed to **reduce irrigation needs** by 15%.

### 9.5.3 *Biogas planning tool in Denmark*

The Danish use case is built around a biogas planning tool designed in the biogas framework and nutrient recycling. Unlike other use cases in the project, it does not apply agronomic or environmental mitigation measures directly at farm level. Its role is rather to put the identified mitigation measures into practice in a different sense, by translating them into user-defined specifications and turning them into quantified outputs that can be examined and compared.

In effect, the DSS sits between mitigation measures on one side and impact-related KPIs on the other. Users can adjust the conditions they feed into the system and observe how different strategic choices ripple through to environmental and agronomic performance. It is, at its core, a tool for structured exploration.

**Mitigation measures as input conditions**: Within the DSS, mitigation measures do not appear as fixed prescriptions. Instead, they take the form of configurable conditions and assumptions that the user sets at the outset. These might include, for instance, substituting mineral fertilisers with digestate derived from biogas production, selecting particular feedstock mixes or nutrient management approaches, deciding where a biogas plant should be located in relation to available feedstocks and nutrient-deficient soils, setting assumptions about transport distances for both feedstock and digestate, or comparing scenarios that reflect different management or logistical strategies.

All of these correspond to mitigation measures described in the present work, particularly those concerning biogas systems and nutrient recycling. The difference is that here they are tested virtually, through the model, rather than put into practice in the field.

KPIs as outputs: Once the user has defined their input conditions, the DSS calculates a set of impact-related KPIs as specified in D2.2. This allows users to gauge the likely consequences of whichever mitigation-oriented strategy they are exploring. Depending on the scenario in question, the outputs may include:

- KPI.EV.02.02 Farm GHG emissions – Capturing the effects of fertiliser substitution, transport distances and feedstock logistics.
- KPI.AG.02.01 Fertiliser N-use efficiency – Reflecting the improved nutrient utilisation that can come from applying digestate.
- KPI.AG.03.01 Soil organic matter and carbon – Tied to the longer-term soil quality implications of using organic fertilisers.
- KPI.AG.03.03 Nitrates | KPI.AG.03.04 Available P – Nitrogen and phosphorus losses associated with alternative approaches to nutrient management.
- KPI.EC.01 Economic performance indicators – help users weigh environmental gains against economic considerations.

It is worth emphasising that these outputs are scenario-based estimations rather than definitive predictions. Their purpose is to enable meaningful comparison between different mitigation-oriented choices, not to deliver a single authoritative answer. Rather than applying mitigation measures itself, the DSS demonstrates how such strategies can be explored, set against one another and evaluated through a digital tool. By connecting user-defined, mitigation-related specifications with a coherent set of harmonised KPIs, the DSS enables users to anticipate potential environmental and agronomic effects before committing to a course of action, identify where competing objectives may pull in different directions, and make more informed decisions ahead of any real-world implementation.

### 9.5.4 *Agrivoltaic systems of Fattoria Sociale del Circeo*

This Italian use case focuses on the integration of agrivoltaic systems, with particular attention to the agronomic assessment, soil management, operational constraints, and the adaptation of farming activities under renewable energy infrastructures. Field demonstrations involve autonomous driving technologies, precision guidance systems, agricultural robotics, and drones developed and evaluated with the support of project partners, including Topcon Positioning Italy and Marchegiani Trattori, to evaluate their potential contribution to safer and more efficient agricultural operations in agrivoltaic environments.

The ongoing pilot, demonstration, and testing activities may provide preliminary evidence and context-specific insights that can support a qualitative interpretation of the following **mitigation measures** and their related KPIs:

- KPI.AG.01.03 Reduction of solar radiation and leaf area index | KPI.AG.01.01 Critical plant density | KPI.AG.01.02 Critical biomass density — Agrivoltaic systems may reduce photosynthetically active radiation (PAR), potentially affecting crop growth and productivity. Potential mitigation measures include **optimized PV infrastructure design and adaptive crop management approaches**, such as the selection of crop types compatible with shaded conditions. The ongoing pilot activities within the Italian use case may provide preliminary evidence to support future assessment of biomass development, plant density, and shading effects under agrivoltaic conditions.
- KPI.EV.01.05 Soil water-holding capacity (WHC) | KPI.EV.01.02 Soil pH | KPI.EV.01.03 Electric conductivity — Agrivoltaic shading may influence soil moisture dynamics and evapotranspiration patterns. Potential mitigation measures may include **precision field management approaches supported by autonomous and assisted guidance technologies** to optimize field operations and reduce unnecessary soil disturbance. **Periodic soil monitoring** may support the identification of potential changes in soil physical and chemical conditions. The ongoing pilot and demonstration activities may provide useful indications to support future assessment of soil-related dynamics in agrivoltaic environments.
- KPI.EV.02.02 Farm GHG emissions | KPI.EN.14 PV performance in an agrivoltaic system — The adoption of autonomous and precision-guided machinery may potentially contribute to reducing unnecessary field passes, fuel consumption, and operational inefficiencies. Potential mitigation measures include the **optimization of machinery trajectories and field operations** under agrivoltaic conditions. Considerations related to renewable energy integration and agrivoltaic performance should be regarded as exploratory and context-specific to the Italian use case. The pilot activities may contribute to generating preliminary evidence to support future evaluation of operational efficiency and agrivoltaic system performance.

- KPI.EV.02.01 Soil compaction | KPI.AG.02.01 Fertilizer N-use efficiency — Repeated machinery operations may contribute to soil compaction and inefficient input use. Potential mitigation measures may rely on **precision farming approaches enabled by assisted and autonomous guidance systems**, with the aim of reducing overlaps and improving operational accuracy during agricultural practices. The ongoing testing activities may provide preliminary indications regarding the potential contribution of precision guidance technologies to reducing soil disturbance and improving input-use efficiency.
- KPI.SC.01 Farmer acceptance and technology uptake — Demonstration and field-testing activities may contribute to **increasing awareness, confidence, and knowledge exchange** regarding autonomous and robotic solutions among farmers and local stakeholders, supporting the potential adoption of innovative technologies in agrivoltaic environments. The demonstration activities carried out within the Italian use case may provide useful evidence on stakeholder engagement and the practical acceptance of innovative agrivoltaic solutions.

## 9.6 Policy and regulatory frameworks

Effective policy and regulatory frameworks are essential to ensure that renewable energy systems can be integrated into agricultural landscapes in a balanced and sustainable manner. While cooperation between farmers, developers and local actors provides the social foundation for successful deployment, coherent regulatory structures create the legal and institutional conditions needed for this cooperation to function. Clear, consistent and context-appropriate rules are therefore fundamental to supporting renewable energy development without compromising agricultural viability, land stewardship or rural community interests.

Current regulatory environments often present challenges for integrating renewable energy in agricultural areas. These may include uncertainties regarding land-use classification, limited guidance on how to maintain agricultural activity alongside energy infrastructure, complex permitting procedures or insufficient consideration of soil protection, biodiversity conservation or farm operational needs. In some contexts, regulations do not yet clearly differentiate between ground-mounted solar systems, agrivoltaic configurations, wind installations or the use of digestate from anaerobic digestion, despite the distinct interactions each of these technologies has with agricultural systems. As a result, farmers and developers may face administrative burdens, unclear responsibilities or conflicting requirements.

A supportive policy framework should therefore enable renewable energy systems to coexist with productive agriculture by providing clear criteria for siting, design and management. This includes establishing guidance on soil protection measures, vegetation management, access for agricultural machinery, grazing compatibility, digestate application standards and biodiversity enhancement opportunities. Policies that explicitly recognise multifunctional land use, where energy generation and agricultural production occur simultaneously, can facilitate the adoption of context-adapted solutions and reduce the perception of competition for land.

Regulatory frameworks also play a key role in ensuring transparency and fairness. Clear rules on contractual arrangements, benefit-sharing mechanisms, environmental safeguards and monitoring obligations help align stakeholder expectations and reduce the risks associated with long-term project implementation. Local and regional authorities contribute to this process by interpreting regulations in a way that reflects territorial priorities, supporting balanced land-use planning and fostering community engagement.

Finally, policies can encourage innovation by allowing flexibility in how renewable technologies are deployed in agricultural settings. Enabling pilot projects, adaptive management approaches and context-sensitive design standards can support the development of infrastructures that fit local agronomic, environmental and social conditions, rather than applying uniform requirements that may not be appropriate for all landscapes.

Overall, well-designed policy and regulatory frameworks are essential to unlocking the potential of renewable energy in agriculture. By providing clarity, consistency and support for multifunctional land use, they create the conditions for effective cooperation, successful mitigation of impacts and the sustainable deployment of renewable energy systems across rural areas.

# 10. CONCLUSIONS AND RECOMMENDATIONS

## 10.1 Main findings per RES

Across all renewable energy systems examined, the analysis shows that their integration into agricultural landscapes generates a combination of opportunities and challenges that are highly dependent on local conditions, infrastructure design and management practices. Positive effects, such as reduced reliance on fossil fuels, improved resource efficiency, diversified farm income or enhanced vegetation cover, can coexist with risks related to soil disturbance, changes in vegetation structure, biodiversity shifts or concerns regarding land availability and landscape perception. This confirms that renewable energy deployment in agriculture is inherently context-specific and requires tailored planning and evaluation.

- For **solar photovoltaic installations** on agricultural land, the findings indicate that shading patterns and ground occupation influence microclimatic conditions, vegetation development and soil processes. While ecological ground management under panels can reduce erosion and support biodiversity, installation and maintenance activities may disrupt soil structure or constrain access for agricultural machinery. The degree to which these impacts are beneficial or adverse depends on site characteristics, panel configuration and management choices. **Agrivoltaic systems**, in contrast, demonstrate considerable potential for multifunctional land use. Partial shading can moderate extreme climatic conditions and, under certain circumstances, improve water-use efficiency or reduce crop stress, although this varies widely depending on crop species, local climate and design parameters such as panel height, spacing and orientation. However, the operational complexity of agrivoltaic systems is greater than that of conventional PV, and long-term evidence remains limited, highlighting the importance of continuous monitoring and adaptive management to assess both productivity and environmental performance.
- **Wind energy systems** generally occupy only a small fraction of agricultural land, allowing farming activities to continue around the infrastructure. Nevertheless, construction and maintenance operations can lead to localised soil compaction or vegetation disturbance, and potential effects on fauna, particularly birds and bats, require careful consideration. Social acceptance often depends on landscape integration, perceived fairness and the extent to which local benefits are recognised, indicating that visual and community-related factors can be as influential as biophysical impacts.
- **Anaerobic digestion** interacts with agricultural systems primarily through the use of digestate as a fertiliser or organic amendment. When applied correctly, digestate can support soil fertility, enhance nutrient cycling and reduce dependence on synthetic fertilisers, contributing to a more circular nutrient economy. However, its composition is variable, and risks such as nutrient losses, emissions or inappropriate application must be managed carefully. The benefits of digestate use therefore depend strongly on adequate storage, timing, dosage and incorporation methods.
- **Bioenergy systems**, concretely thermochemical processing of biomass, can provide a stable and controllable renewable energy source that complements intermittent technologies such as solar and wind. In agricultural contexts, their impacts are strongly linked to biomass sourcing and land management practices. The use of agricultural and forestry residues can support circular resource use and reduce waste, while also creating opportunities for rural employment and local value chains. However, excessive biomass harvesting may lead to soil erosion, nutrient depletion, carbon stock reduction and biodiversity loss, particularly where residues are removed beyond sustainable levels or forest management is intensified. The environmental performance of bioenergy systems also depends on factors such as transport distances, feedstock pre-treatment and conversion efficiency, as thermochemical processes can generate air pollutants if poorly managed. Sustainable outcomes

therefore rely on responsible biomass sourcing, protection of soil functions, efficient emission control technologies and the prioritisation of residue-based feedstocks over dedicated energy crops or further land conversion.

- Micro-hydro systems, and more specifically micro-pumped hydro-energy storage (micro-PHES), offer opportunities to improve on-farm energy management by using existing water infrastructure such as irrigation systems, farm dams or small hydraulic networks. These systems can provide long-duration energy storage, improve renewable energy integration and reduce dependence on fossil fuels for irrigation or electricity supply, often with relatively limited land occupation when existing reservoirs are used. Compared with conventional battery storage, micro-PHES systems may offer longer operational lifespans and lower impacts in several environmental categories. Nevertheless, their performance and economic feasibility remain highly dependent on site-specific conditions, infrastructure availability and technological optimisation, as the technology is still at an early development stage. Environmental concerns mainly arise when new reservoirs or hydraulic modifications are required, potentially affecting hydrology, landscape quality and local ecosystems, while visual and noise impacts may also influence social acceptance.

## 10.2 Cross-sectoral recommendations for sustainable deployment

The findings of this Deliverable highlight that the sustainable integration of renewable energy systems into agricultural landscapes requires a coordinated approach that addresses agronomic, environmental, social and governance-related dimensions simultaneously. A first recommendation concerns the need to adopt a multifunctional land-use perspective in all stages of project development. Renewable energy infrastructures should be planned and designed in ways that respect agricultural practices, protect soil functions, maintain or enhance biodiversity, and minimise unnecessary land-use conflicts. Achieving this requires context-specific assessments that consider local climate, crop systems, soil characteristics and landscape structure, ensuring that renewable technologies are adapted to the sites in which they operate.

The second recommendation relates to monitoring. Transparent, continuous and practical monitoring of agronomic, environmental, soil and social indicators is essential for evaluating the performance of renewable systems and for supporting adaptive management. Indicators should be feasible for farmers and land managers to measure, using accessible and cost-effective methods that promote direct engagement and support informed decision-making. Embedding monitoring as a standard practice across deployments helps identify emerging issues, validate the effectiveness of mitigation measures and build long-term trust among stakeholders.

Strengthening cooperation among farmers, developers, local authorities and communities is another central recommendation. Collaborative planning processes, early engagement and open communication help align expectations, address operational needs and reduce social tensions. Fair and transparent benefit-sharing arrangements further enhance acceptance and ensure that local actors perceive renewable energy development as compatible with agricultural viability and community well-being. Cooperation also reinforces the applicability of monitoring frameworks, as shared understanding of system behaviour facilitates coordinated responses to observed impacts.

Education and awareness-raising also play an important role in supporting sustainable deployment. Providing farmers, local residents and other stakeholders with clear and accessible information on potential impacts, monitoring approaches and mitigation options increases confidence and enables more informed decision-making. Training initiatives, demonstration sites and knowledge-sharing platforms can strengthen local capacity, encourage the adoption of good practices and improve understanding of how renewable energy systems interact with agricultural landscapes. These efforts contribute to greater acceptance and help consolidate long-term cooperation.

On the other hand, policy and regulatory frameworks should provide clarity, predictability and flexibility to support the sustainable deployment of renewable energy in agricultural environments. This includes simplifying administrative procedures, offering clear guidance on soil and biodiversity protection, recognising multifunctional land-use models and enabling innovative configurations such as agrivoltaics. Policies should also encourage the responsible use of digestate and other circular strategies, while ensuring that risks to soil and water quality are adequately managed. Context-sensitive regulatory frameworks can reduce barriers, support agricultural resilience and motivate renewable energy developers to adopt best practices.

Finally, cross-sectoral coordination between agricultural, energy, environmental and land-use planning authorities is needed to align objectives and maximise synergies. Integrating renewable energy considerations into rural development strategies and agricultural policy objectives can help ensure that the energy transition strengthens, rather than competes with, sustainable food production and the ecological functioning of rural landscapes. This coordination provides the foundation for coherent planning and supports the systemic perspective required for long-term sustainability.

## 10.3 Expected integration with WP5/WP6 outcomes

Deliverable 2.1 of the HarvREASt project established a typology of RES integration in agriculture and an initial identification of impact categories. On this basis, Deliverable 4.5 delves into the agronomic, environmental, and social effects of the main renewable technologies on agricultural systems. Its purpose is to gather existing scientific evidence, analyse impact mechanisms, and evaluate mitigation measures that can reduce risks and improve coexistence between energy and agriculture. It also contributes to the definition of common agronomic indicators (agro-KPIs), that were developed in Deliverable 4.2, which are essential for evaluating the interaction between agricultural production and renewables.

The agronomic indicators defined in this deliverable will be used in later phases of the project, where they will be integrated into the analytical tools developed in WP5 and WP6. This will allow for a systematic assessment of which technological and territorial configurations favour an energy transition compatible with the productive and ecological sustainability of European agriculture.

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# 12. ANNEXES

## 12.1 Annex 1 – DATABASE OF THE BIOMETHANE POTENTIAL FROM DIFFERENT FEEDSTOCKS

| ID | Category | Feedstock | Location | Mixture | Total Solids (g/kg) | Promedio TS | Volatile Solids (g/kg) | Promedio VS | %VS PROMEDIO | PROMEDIO %VS | BMP (L/kg SV) | Promedio BMP (L/Kg SV) | L de metano producidos en el experimento (mL/kg de muestra) | Promedio L | BMP (L/kg ST) | % Methane | Promedio Methane % | Biodegradability (%) | Promedio Biodegradability (%) | Biogas potential (mL/kg VS) | Promedio Biogas potential (mL/kg VS) | BMP Teórico VS: BMP = YCH4 * VS YCH4 = 0,35Lm/kg SV BMP = L/kg de muestra | Promedio BMP Teórico | % de desviación (experimental vs teórico) %=Exp/teórico | Promedio % de desviación (Factor de Corrección) | URL - DOI - Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | Pig fatteners, faeces | Denmark | 1:1 Inoculum | 223,39 | | 193,97 | | 87% | | 356 | | 69,05 | | 69,05 | | | 67% | | | | 67,89 | | 102% | | doi:10.1016/j.biombioe.2003.08.008 |
| 2 | | Pig Manure | China | Pure | 281,40 | | 222,6 | | 79% | | 253,8 | | 56,50 | | 56,50 | | | | | 385000 | | 77,91 | | 73% | | doi:10.1016/j.renene.2011.05.002 |
| 3 | | Pig Manure | Ireland | Pure | 126 | | 93 | | 74% | | 279,8 | | 26,02 | | 26,02 | | | | | | | 32,55 | | 80% | | doi:10.1016/j.biortech.2011.03.009 |
| 4 | | Pig Manure | Ireland | 1:0 | 43,5 | | 27,2 | | 63% | | | | 14,88 | | 14,88 | | | | | | | | | | | https://doi.org/10.1016/j.wasman.2020.10.041 |
| 5 | | Pig Manure | Ireland | 50:50 Inoculum | 256,2 | | 211,4 | | 83% | | 213 | | 45,03 | | 45,03 | | | | | | | 73,99 | | 61% | | https://doi.org/10.1016/j.wasman.2018.07.049 |
| 6 | 1 | Pig Manure | Thailand | | 253 | 233,41 | 716 | 330,83 | | 78% | 362 | 267,08 | 259,19 | 70,26 | 259,19 | | 65,3 | | 0,67 | | 440000 | 250,6 | 111,34 | 103% | 76% | doi:10.1016/j.biombioe.2010.02.018 |
| 7 | | Pig Manure | | | | | 58,7 | | 74% | | 144 | | 8,45 | | 8,45 | | | | | | | 20,545 | | 41% | | https://upcommons.upc.edu/bitstream/handle/2117/26888/llintersymAD-BArcelona%20doc.pdf |
| 8 | | Pig Manure | Mexico | | 272 | | 808 | | | | | | 25,61 | | 25,61 | | | | | | | | | | | https://doi.org/10.1016/j.renene.2022.09.068 |
| 9 | | Pig Manure | | | | | 780 | | | | 205 | | 159,90 | | 159,90 | | | | | | | 273 | | 59% | | https://doi.org/10.1016/j.jwpe.2023.103877 |
| 10 | | Pig Manure | China | | 335 | | 259 | | 77% | | | | 21,24 | | 21,24 | | | | | | | | | | | https://doi.org/10.1016/j.cej.2024.153988 |
| 11 | | Pig Manure | | | 310,2 | | 269,3 | | 87% | | 323 | | 86,98 | | 86,98 | 65,3 | | | | 495000 | | 94,255 | | 92% | | http://dx.doi.org/10.1016/j.wasman.2015.10.021 |
| 12 | | Cattle, dairy faeces | Denmark | Hay from clover and minerals | | | 902,7 | | | | 190 | | 171,51 | | 171,51 | | | 0,21 | | | | 315,945 | | 54% | | doi:10.1016/j.biombioe.2003.08.008 |
| 13 | | Cow Manure | Jordan | Pure | 143,8 | | 120,7 | | 84% | | | | 10,58 | | 10,58 | | | | | | | 42,245 | | 25% | | https://doi.org/10.1016/j.cscee.2023.100589 |
| 14 | | Cow Manure | Netherlands | Pure | 200 | | 170 | | 85% | | 160 | | 27,20 | | 27,20 | | | | | | | 59,5 | | 46% | | https://doi.org/10.1016/j.renene.2020.02.041 |
| 15 | | Cow Manure | China | 4:0 | 217,20 | | 167,30 | | 77% | | | | 13,72 | | 13,72 | | | | | | | 58,555 | | 23% | | https://doi.org/10.1016/j.eti.2023.103389 |
| 16 | | Cow Manure | Norway | Pure | | | 748 | | | | 180 | | 134,64 | | 134,64 | 65 | | | | | | 261,8 | | 51% | | http://dx.doi.org/10.1016/j.wasman.2014.04.011 |
| 17 | 2 | Cow Manure | Finland | Pure | | 210,95 | | 311,51 | 82% | 77% | 212 | 230,75 | 9,96 | 46,98 | 9,96 | | 66,03 | | 0,21 | | 203000 | 16,45 | 89,26 | 61% | 63% | http://dx.doi.org/10.1016/j.fuel.2012.12.069 |
| 18 | | Cow Manure | China | Pure | 346,6 | | 195,2 | | 56% | | | | 27,29 | | 27,29 | | | | | 210000 | | 68,32 | | 40% | | doi:10.1016/j.renene.2011.05.002 |
| 19 | | Cow Manure | Spain | Pure | 221,6 | | 208,5 | | 94% | | 317 | | 66,09 | | 66,09 | | | | | | | 72,975 | | 91% | | http://dx.doi.org/10.1016/j.biortech.2014.02.007 |
| 20 | | Cow Manure | New Zeland | 1:2 Cow Manure-Incoculum | 172 | | 103 | | 60% | | | | 8,45 | | 8,45 | | | | | | | 36,05 | | 23% | | https://doi.org/10.1016/j.fuel.2024.133458 |
| 21 | | Cow Manure | China | | 217,31 | | 188,16 | | 87% | | 352,22 | | 66,27 | | 66,27 | | | | | | | 65,856 | | 101% | | https://doi.org/10.1016/j.biortech.2021.125205 |
| 22 | | Cow Manure | | | 169,1 | | | | 61% | | 204 | | 20,91 | | 20,91 | 69,1 | | | | 295000 | | 35,875 | | 58% | | http://dx.doi.org/10.1016/j.wasman.2015.10.021 |
| 23 | | Cow Manure | | Pure | | | | | 88% | | | | 7,14 | | 7,14 | 64 | | | | 104000 | | 37,52 | | 19% | | https://doi.org/10.1016/j.serj.2018.03.003 |
| 24 | | Poultry Manure | Brasil | 0,5 food/inoculum | | | | | 37% | | | | 98,74 | | 98,74 | | | | | | | 114,45 | | 86% | | https://doi.org/10.1016/j.biortech.2019.122588 |
| 25 | | Poultry Manure | Canada | Pure | | | | | 80% | | | | 71,54 | | 71,54 | | | | | | | 189,7 | | 38% | | https://doi.org/10.1016/j.bcab.2020.101605 |
| 26 | | Poultry Manure | Canada | Pure | 264,3 | | 174,3 | | 66% | | 153 | | 26,67 | | 26,67 | | | | | | | 61,005 | | 44% | | https://doi.org/10.1016/j.jenvman.2022.115717 |
| 27 | | Poultry Manure | Jordan | Pure | 263,5 | | 227 | | 86% | | 285 | | 64,70 | | 64,70 | | | | | | | 79,45 | | 81% | | https://doi.org/10.1016/j.rineng.2024.102040 |
| 28 | | Poultry Manure | Turkey | | 268 | | 175,75 | | 66% | | 241,67 | | 42,47 | | 42,47 | | | | | | | 61,5125 | | 69% | | http://dx.doi.org/10.1016/j.ibiod.2016.10.058 |
| 29 | 3 | Poultry Manure | | | 250 | 319,98 | 698 | 343,35 | | 66% | 493 | 268,78 | 344,11 | 83,86 | 344,11 | | 64,3 | | 61 | | 368200,00 | 244,3 | 115,91 | 141% | 72% | http://dx.doi.org/10.1016/j.biortech.2014.02.050 |
| 30 | | Poultry Manure | Poland | Pure | 296,12 | | 221,91 | | 75% | | 181 | | 40,17 | | 40,17 | 67 | | | | | | 77,6685 | | 52% | | http://dx.doi.org/10.1016/j.renene.2016.07.046 |
| 31 | | Poultry Manure | China | | | | | | 59% | | | | 12,88 | | 12,88 | 64,8 | | 61 | | | | 9,45 | | 136% | | http://dx.doi.org/10.1016/j.biortech.2013.09.091 |
| 32 | | Poultry Manure | China | | 268 | | 623 | | | | | | 79,06 | | 79,06 | | | | | 311400 | | 218,05 | | 36% | | http://dx.doi.org/10.1016/j.biortech.2012.06.058 |
| 33 | | Poultry Manure | Bangladesh | | 271,5 | | 151,8 | | 56% | | | | 19,16 | | 19,16 | | | | | | | 53,13 | | 36% | | https://doi.org/10.1016/j.heliyon.2025.e42687 |
| 34 | | Poultry Manure | | | 678,4 | | 475 | | 70% | | 259 | | 123,03 | | 123,03 | 61,1 | | | | 425000 | | 166,25 | | 74% | | http://dx.doi.org/10.1016/j.wasman.2015.10.021 |
| 35 | | OFMSW | Malasya | Pure | 221 | | 296 | | | | 396 | | 117,22 | | 117,22 | | | | | | | 103,6 | | 113% | | https://doi.org/10.1016/j.scitotenv.2021.145961 |
| 36 | | OFMSW | India | Pure | | | | | | | | | 0,00 | | 0,00 | 60 | | | | 228000 | | 330,435 | | 0% | | https://doi.org/10.1016/j.ijhydene.2018.02.072 |
| 37 | | OFMSW | | Pure | 187 | | 175 | | 94% | | | | 0,00 | | 0,00 | | | | | 700000 | | 61,25 | | 0% | | http://dx.doi.org/10.1016/j.renene.2015.12.029 |
| 38 | | OFMSW | China | Pure | 199,93 | | 180,43 | | 90% | | 575 | | 103,75 | | 103,75 | | | | | | | 63,1505 | | 164% | | doi:10.1016/j.wasman.2011.09.027 |
| 39 | | OFMSW | | Pure | 166 | | 155 | | 93% | | | | 0,00 | | 0,00 | | | | | | | 54,25 | | 0% | | doi:10.1016/j.biortech.2010.07.122 |
| 40 | | OFMSW | Japon | | | | 903 | | | | | | 171,57 | | 171,57 | | | | | 370000 | | 316,05 | | 54% | | https://doi.org/10.1016/S0922-338X(97)82999-6 |
| 41 | 4 | OFMSW | Spain | | | 232,99 | 698 | 340,21 | 80% | 85% | 110 | 382,77 | 76,78 | 95,07 | 76,78 | | 60 | | | | 432666,67 | 244,3 | 134,17 | 31% | 86% | https://doi.org/10.1016/j.biortech.2006.07.008 |
| 42 | | OFMSW | Republic of Korea | | 181 | | 171 | | 94% | | 479,5 | | 81,99 | | 81,99 | | | | | | | 59,85 | | 137% | | https://doi.org/10.1016/j.biortech.2011.01.082 |
| 43 | | OFMSW - mechanically separated | | | 665 | | 352,45 | | 53% | | 300 | | 105,74 | | 105,74 | | | | | | | 123,3575 | | 86% | | https://doi.org/10.1016/j.rser.2018.05.051 |
| 44 | | OFMSW - sorted at source | | | 200 | | 160 | | 80% | | 450 | | 72,00 | | 72,00 | | | | | | | 56 | | 129% | | https://doi.org/10.1016/j.rser.2018.05.051 |
| 45 | | OFMSW - separately collected | | | 161 | | 127,834 | | 79% | | 500 | | 63,92 | | 63,92 | | | | | | | 44,7419 | | 143% | | https://doi.org/10.1016/j.rser.2018.05.051 |
| 46 | | OFMSW | | | 126,5 | | 112,9645 | | 89% | | 255 | | 28,81 | | 28,81 | | | | | | | 39,537575 | | 73% | | https://doi.org/10.1016/j.biortech.2017.09.020 |
| 47 | | OFMSW | | | 227,5 | | 209,0725 | | 92% | | 495 | | 103,49 | | 103,49 | | | | | | | 73,175375 | | 141% | | https://doi.org/10.1016/j.biortech.2017.09.020 |
| 48 | | OFMSW | | | 228 | | 882 | | | | 460 | | 405,72 | | 405,72 | | | | | | | 308,7 | | 131% | | https://doi.org/10.1016/j.wasman.2016.01.041 |
| 49 | | ABP | Spain | Pure | 377,32 | | 361,87 | | 96% | | 254,28 | | 92,02 | | 92,02 | 62,37 | | | | 407433,3 | | 126,6533333 | | 73% | | https://doi.org/10.1016/j.rineng.2024.103389 |
| 50 | | ABP | Ireland | Pure | 279 | | | | | | 465,34 | | 443,00 | | 443,00 | | | 95,73 | | | | 333,2 | | 133% | | https://doi.org/10.1016/j.wasman.2015.10.013 |
| 51 | | ABP | Ireland | Pure | 283 | | 260 | | 92% | | 600 | | 156,00 | | 156,00 | | | | | 1000000 | | 91 | | 171% | | https://doi.org/10.1016/j.bej.2007.11.019 |
| 52 | | ABP | USA | | | | 5,8 | | 88% | | | | 0,66 | | 0,66 | | | | | | | 2,03 | | 33% | | https://doi.org/10.1016/j.renene.2018.03.076 |
| 53 | 5 | ABP | | | | 351,41 | | 279,78 | 67% | 78% | 390 | 514,17 | 259,74 | 266,50 | 259,74 | | 65,68 | | 95,73 | | 703716,7 | 233,1 | 181,74 | 111% | 135% | https://doi.org/10.1016/j.biortech.2012.04.038 |
| 54 | | ABP | | | 220 | | | | | | 500 | | 455,00 | | 455,00 | | | | | | | 318,5 | | 143% | | https://doi.org/10.1016/S0960-8524(01)00199-7 |
| 55 | | ABP | Greece | | 288 | | 280 | | 97% | | | | 212,52 | | 212,52 | | | | | | | 98 | | 217% | | https://doi.org/10.1016/j.wasman.2017.07.009 |
| 56 | | ABP | Spain | | 507 | | 489 | | 96% | | 580 | | 283,62 | | 283,62 | | | | | | | 171,15 | | 166% | | https://doi.org/10.1016/j.wasman.2011.02.014 |
| 57 | | ABP | Ireland | | 539 | | | | | | | | 641,79 | | 641,79 | 69 | | | | | | 345,1 | | 186% | | https://doi.org/10.1016/j.renene.2016.05.068 |
| 58 | | ABP | Finland | | 318 | | 282 | | 89% | | 428 | | 120,70 | | 120,70 | | | | | | | 98,7 | | 122% | | https://doi.org/10.1016/j.biortech.2011.09.104 |
| 59 | | Straw | Spain | Particle size: 3–5 cm | 895 | | 821 | | 92% | | 239 | | 196,22 | | 196,22 | | | | | | | 287,35 | | 68% | | https://doi.org/10.1016/j.cej.2013.08.041 |
| 60 | | Wheat Straw 1mm | Denmark | | | | 959 | | | | 161 | | 154,40 | | 154,40 | | | 45 | | | | 335,65 | | 46% | | https://doi.org/10.1016/j.biombioe.2003.08.008 |
| 61 | | Straw | Denmark | | 916 | | 875 | | 96% | | 297 | | 259,88 | | 259,88 | | | 69 | | | | 306,25 | | 85% | | https://doi.org/10.1016/j.biortech.2008.11.011 |
| 62 | | Rice Straw | | | 717,4 | | 591,2 | | 82% | | 170 | | 100,50 | | 100,50 | | | | | 325000 | | 206,92 | | 49% | | https://doi.org/10.1016/j.heliyon.2025.e42687 |
| 63 | 6 | Rice Straw | China | 20% inoculum | 868 | 835,83 | 844,564 | 802,17 | 97% | 91% | 155,5 | 212,94 | 131,33 | 139,54 | 131,33 | | 59,09 | | 57 | | 362612,5 | 295,5974 | 280,761 | 44% | 61% | https://doi.org/10.1016/j.biteb.2020.100509 |
| 64 | | Rice Straw | | | 847 | | 739 | | 87% | | 0 | | 0,00 | | 0,00 | 58,3 | | | | 334000 | | 258,65 | | 0% | | https://doi.org/10.1016/j.biortech.2022.127391 |
| 65 | | Maize Straw | Poland | | 546 | | 507,78 | | 93% | | 193 | | 98,00 | | 98,00 | 48,97 | | | | 391450 | | 177,723 | | 55% | | https://doi.org/10.3390/ma12233848 |
| 66 | | Wheat Straw | | | | | 950 | | | | 308 | | 292,60 | | 292,60 | | | | | | | 332,5 | | 88% | | https://doi.org/10.1007/s12155-020-10126-7 |
| 67 | | Rice Straw | China | | 937,2 | | 831,8 | | 89% | | 0 | | 0,00 | | 0,00 | 70 | | | | 400000 | | 291,13 | | 0% | | https://doi.org/10.1016/j.wasman.2013.05.014 |
| 68 | | Wheat Straw | Sweden | | 960 | | 902,4 | | 94% | | 180 | | 162,43 | | 162,43 | | | | | | | 315,84 | | 51% | | https://doi.org/10.1016/j.biortech.2012.10.117 |

HarvRESt
Greener Farming with RES

## The project

The HarvRESt project 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, HarvRESt seeks 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. HarvRESt will 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 | CONFAGRI |
| | Fattoria Solidale del Circeo | FSDC |
| | Viñas del Vero | VdV |
| | Viñedos del Rio Tajo | VRT |
| | Sorigué | ACSA |
| | Grønn Gårdsenergi AS | GGE |
| | Food & Bio Cluster Denmark | FBCD |
| | Climate KIC | CKIC |
| | HEC Paris | HEC |

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