3 DS ANALYSIS AND AI SCENARIOS FOR DS1

The Spanish Demo Site (DS1) is located in Catalonia, one of the most important wine-producing regions in Europe. Two pilot systems were developed: one at the Raventós Codorníu winery (Penedès area), focusing on the treatment and reuse of winery wastewater, and one at IRTA's Torre Marimon Research Centre (Caldes de Montbui), addressing nitrate-rich groundwater. Both pilots are based on containerised constructed wetlands using aeration and recycled cork as filter media. These innovations respond to the need for more sustainable water and nutrient management in viticulture and agro-industrial contexts, while contributing to circular economy practices by valorising forestry by-products.

3.1 Context and Challenges

The Catalan wine sector faces multiple Nexus-related pressures:

- Water: recurrent droughts and overexploitation of groundwater threaten water availability for viticulture and local communities.
- Energy: conventional water treatment and pumping are energy-intensive, increasing operational costs.
- Food: sustainable water use is critical for maintaining wine production and competitiveness in international markets.
- Ecosystems: fertiliser and pesticide residues, as well as saline discharges, impact soil and freshwater ecosystems.

To address these challenges, two pilot systems were established within DS1:

- DS1A, at the Raventós Codorníu winery (Penedès area), a containerised constructed wetland was installed to treat and reuse winery wastewater.
- DS1B, at IRTA's Torre Marimon Research Centre (Caldes de Montbui), a similar system was adapted for the treatment of nitrate-rich groundwater.

Both pilots demonstrate scalable solutions that integrate water reuse, renewable energy, and circular economy practices while testing the use of recycled cork as a filtration medium.

In Spain, the Institute of Agro-Food Research and Technology (IRTA) at Codorníu and Torre Marimon collaborated with the UPC to test the demosites dedicated to the **valorization of winery effluents through an innovative aerated treatment wetland composed of cork granulates**. The system is engineered to achieve high removal efficiencies for organic matter, nutrients, and pesticides while concurrently valorizing cork residues originating from local cork industries.

These pilots were grounded in the legacy of the ECORKWASTE project, which had already demonstrated the potential of cork as a sustainable filtration medium, particularly for the **removal of nitrate and phosphorus**. Furthermore, it achieved **significant reductions for pesticides such as metalaxyl, chlorpyrifos, and heavy metals like copper**.

Finally, it should be emphasized the contribution of these systems to the circular economy. The valorization of cork by-products not only improves wastewater treatment but also contributes to the preservation of cork oak ecosystems and the creation of green jobs in rural areas.

3.2 Top 3 prioritised solutions

The prioritisation exercise conducted during the Barcelona workshop (28 November 2023) applied the SureNexus MCA tool to 39 candidate solutions. The results show that three practices clearly stood out, each surpassing the minimum threshold score of 50 and emerging as the most promising for the Catalan context.

- **Constructed wetlands with recycled materials (cork)** ranked first, combining wastewater treatment efficiency with circular economy benefits. The use of cork, a by-product of local forestry, was seen as a strong innovation that enhances ecosystem restoration while creating economic opportunities.
- **Vertical flow constructed wetlands** were prioritised in second place, offering high treatment performance and reliability in removing nutrients and pollutants. Their modular design makes them adaptable to different scales, from winery operations to broader agricultural applications.
- **Aerated constructed wetlands** ranked third, including air as an innovative wastewater treatment using an advanced nature-based solutions, to accelerate the efficiency of pollutant removal.

3.3 AI Scenario Results

This section presents the AI-based evaluation of the **four vertical-flow constructed wetland configurations tested in DS1 (Spain), considering two filtering materials (cork vs. gravel) and two operational modes (aerated vs. non-aerated).** The following figures illustrate treatment performance (nitrate and COD removal), energy consumption, greenhouse gas emissions (GHG), and aggregated Nexus indicators derived from normalization procedures. Overall, the sequence of figures provides a step-by-step understanding of how material choice and aeration conditions influence efficiency and WEFE Nexus trade-offs at the Spanish Demo Site.

Figure 7 shows that all scenarios achieve substantial nitrate removal, but the **highest performance occurs in the aerated cork systems**. Scenarios S1 and S5 (Aerated Cork) achieve the highest removal efficiency (~95%). This is attributed to the synergy between aeration (which provides oxygen for nitrification) and cork (which provides an organic carbon source necessary for denitrification).

Gravel-based systems (S2, S4, S6, S8) hover around 40-45% removal, because without the external carbon source that cork provides, the denitrification process is limited. Within each operational mode, **cork consistently performs better than—gravel**, highlighting its viability as a circular-material alternative with comparable pollutant removal capacity.

Figure 8 shows the removal efficiency of Chemical Oxygen Demand (COD), a proxy for organic pollution. The most critical observation is the negative removal (green bars dropping below zero) for all cork scenarios (S1, S3, S5, S7). This indicates that the **cork media degrades, releasing organic matter (leaching effect) into the water rather than removing it**. Gravel scenarios (S2, S4, S6, S8) function effectively as filters, achieving positive removal. Aerated Gravel (S2, S6) performs best (~85%) as oxygen aids in the biological breakdown of organics.

Key Takeaway: Cork media presents a significant trade-off: it aids Nitrogen removal but worsens COD levels due to organic leaching.

Figure 9 compares the operational energy demand of each scenario. All scenarios share the same baseline consumption from pumping, solenoid valves, and the automation system. The key difference is the aeration system (blower), present only in the aerated configurations (S1, S2, S5, S6), which consume 93 kWh/month, whereas the non-aerated systems consume 83.7 kWh/month. The type of media (Cork vs. Gravel) does not impact energy consumption, only the mechanical equipment used. Aeration increases the energy footprint by approximately 11%, which is the "cost" of achieving higher treatment efficiency.

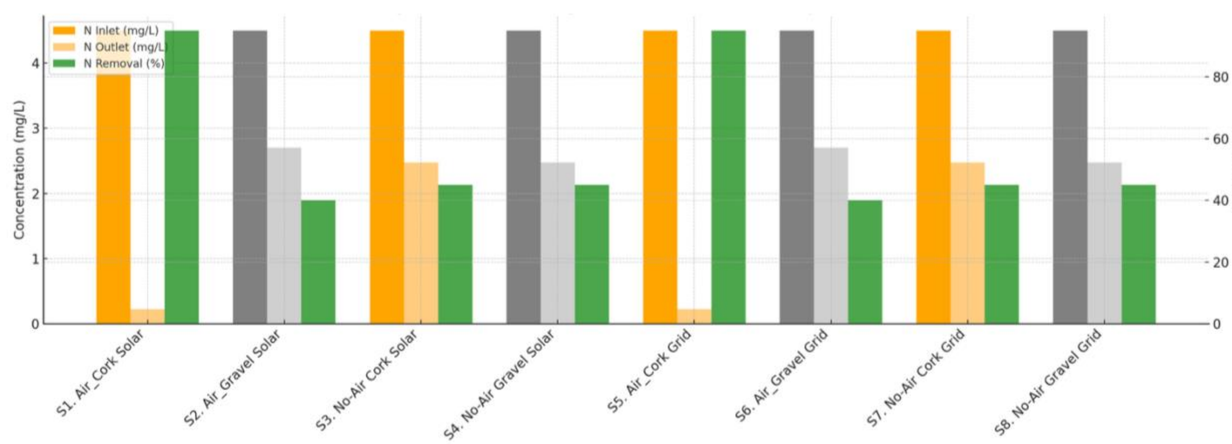

FIGURE 7. RESULTS OF NITRATE REMOVAL WITH VERTICAL TREAMENT WETLAND, DEPENDING ON MATERIAL (CORK VS GRAVEL) AND AERATION (AIR VS NON-AIR).

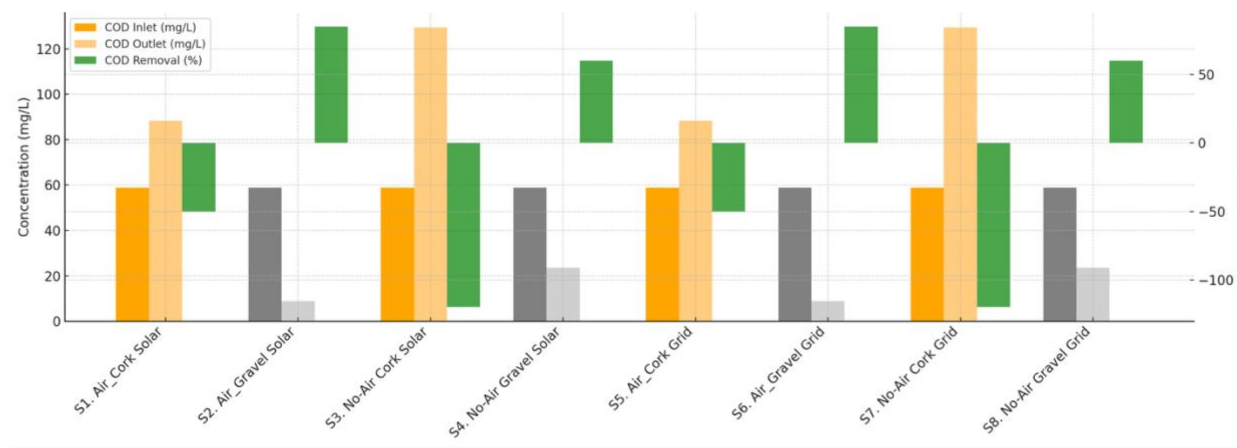

FIGURE 8. RESULTS OF COD REMOVAL WITH VERTICAL TREAMENT WETLAND, DEPENDING ON MATERIAL (CORK VS GRAVEL) AND AERATION (AIR VS NON-AIR).

At the same time, the chart converts energy consumption into Green House Gas (GHG) emissions based on the power source and the type of material (cork or gravel). There is a drastic difference between energy sources. Solar-powered scenarios (S1-S4) emit significantly less CO_2 (ranging from ~21 to 33 kgCO2e) compared to Grid-powered scenarios (S5-S8). Scenario 3 (Non-Aerated Cork, Solar) has the lowest carbon footprint (~20.8 kgCO2e) because it uses the least energy and sources it from renewables.

Key Takeaway: Integrating solar photovoltaics allows for the implementation of energy-intensive processes (like aeration) while maintaining a low carbon profile.

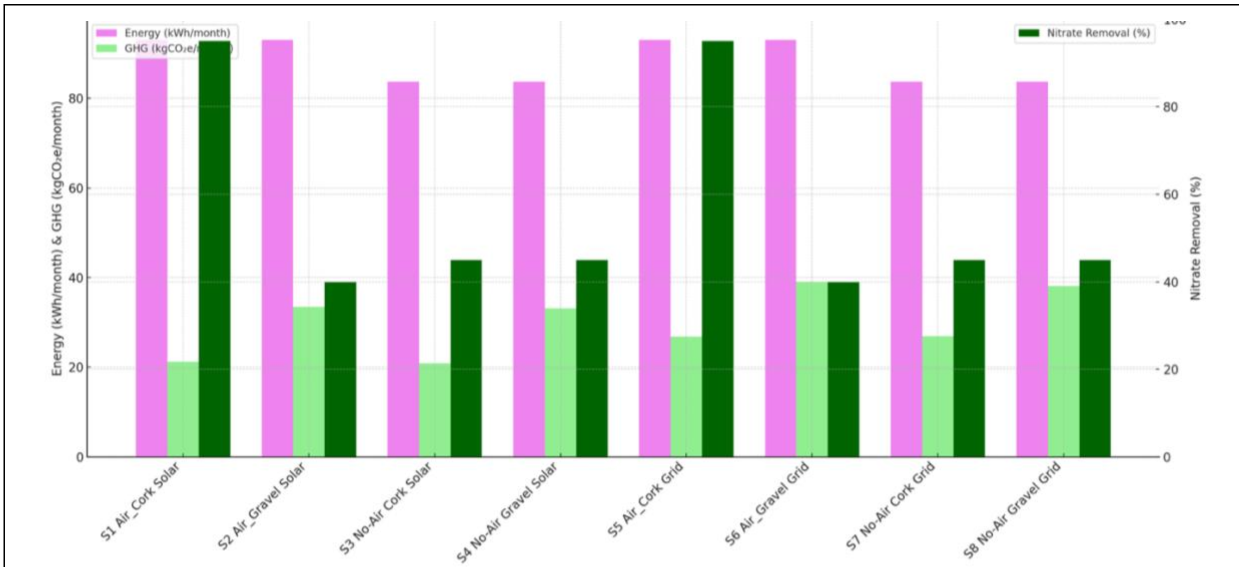

FIGURE 9. RESULTS OF NITRATE REMOVAL WITH VERTICAL TREAMENT WETLAND, AND ENERGY AND GHG EMISSIONS FOR EACH SCENARIO DEPENDING ON MATERIAL (CORK VS GRAVEL) AND AERATION (AIR VS NON-AIR). RESULTS NORMALIZED

To enable a comparable evaluation of heterogeneous variables—energy use, GHG emissions, and pollutant removal performance—the analysis applied a **relative-to-minimum inverse normalization for resource consumption indicators** (energy and GHG), and a **relative-to-maximum direct normalization for treatment performance indicators** (nitrate or COD removal). This approach ensures that variables with different units and magnitudes can be represented together in a single composite index while preserving their physical meaning. For energy and GHG emissions, lower values represent better Nexus performance; therefore, an **inverse normalization** was applied:

$$X_{\text{norm}} = \frac{X_{\min}}{X}.$$

This formulation scales all scenarios between 0 and 1 based on their distance from the best-performing (lowest) case, ensuring that reductions in energy demand or emissions translate into higher normalized scores.For water-quality treatment performance, where higher pollutant removal represents a positive outcome, a **direct relative-to-maximum normalization** was applied:

$$R_{\text{norm}} = \frac{R}{R_{\max}}.$$

This method highlights the scenarios with the highest pollutant removal efficiencies while proportionally representing intermediate and low-performing scenarios. In the case of COD, negative removal values (indicating deterioration) were assigned a normalized score of zero, reflecting an absence of treatment benefit. The resulting normalized indicators were combined in stacked bar charts to construct a **Nexus Performance Index**, enabling an integrated visual comparison of trade-offs between energy use, emissions, and treatment effectiveness across all tested scenarios.

Figure 10 shows the normalized results for Nitrate removal and the energy and GHG emissions associated for each scenario, whereas Figure 11 shows the results for COD removal. **Aerated Cork Solar (S1) shows the highest positive stack due to high Nitrogen removal** and good Energy/GHG scores (Solar). However, it carries a visible red bar below the axis for negative COD removal. Aerated Gravel Solar (S2) shows a balanced positive profile (good COD, moderate N, good Energy) with no negative leaching penalty.

Key Insight: Figure 10 visually demonstrates the trade-offs. S1 is the "high risk/high reward" option (Great N, Bad COD), while Gravel options are "safe" but less effective at Nitrogen removal.

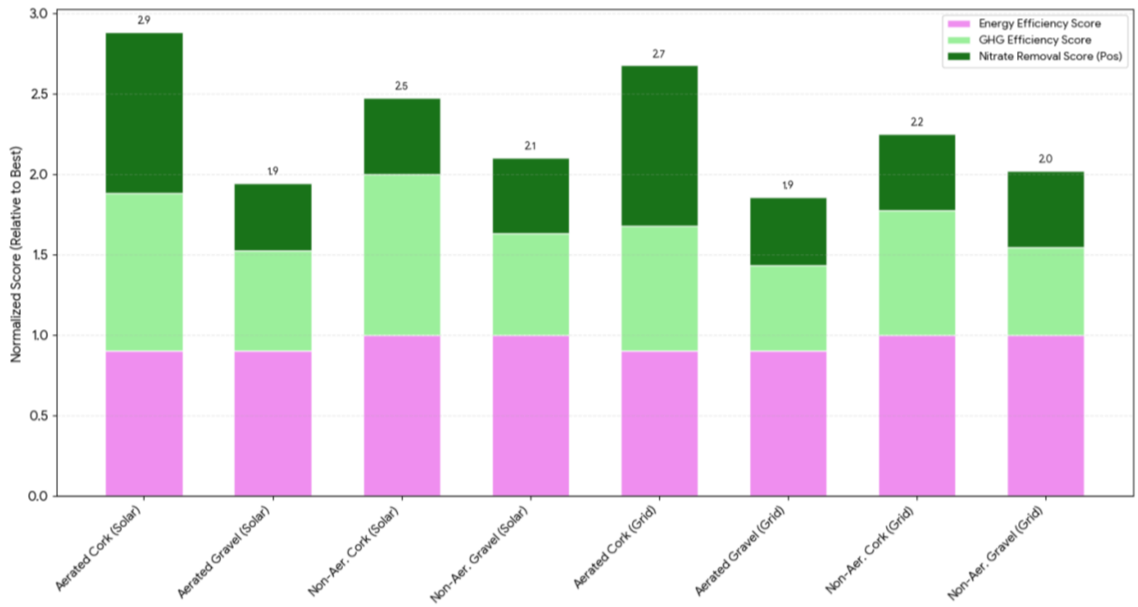

FIGURE 10. RESULTS OF NITRATE REMOVAL WITH VERTICAL TREAMENT WETLAND, AND ENERGY AND GHG EMISSIONS FOR EACH SCENARIO DEPENDING ON MATERIAL (CORK VS GRAVEL) AND AERATION (AIR VS NON-AIR). RESULTS OF NORMALIZED PERFORMANCE IN A STACKED NEXUS INDEX.

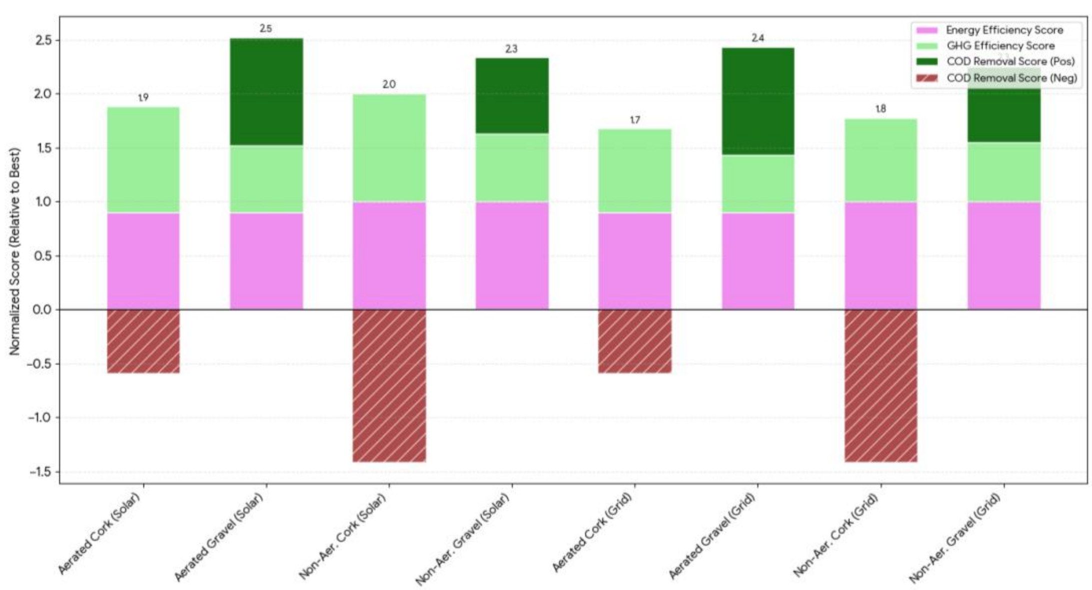

FIGURE 11. RESULTS OF COD REMOVAL WITH VERTICAL TREAMENT WETLAND, DEPENDING ON MATERIAL (CORK VS GRAVEL) AND AERATION (AIR VS NON-AIR). NORMALIZED PERFORMANCE RESULTS IN A STACKED NEXUS INDEX.

An interactive chart showing nitrate removal versus energy use and GHG emissions across scenarios can be downloaded here.

Figure 12 shows a radar chart overlaying the performance shapes of the scenarios. S1 (Aerated Cork Solar) covers the largest total area on the chart, confirming its status as the most effective overall solution despite the COD trade-off. Considering the shape the chart clearly shows two distinct shapes:

- **Cork Scenarios**: Skew heavily toward the "Nitrate Removal" axis but retract at the "COD Removal" axis.
- **Gravel Scenarios**: Skew toward "COD Removal" but lack reach in "Nitrate Removal."

Figure 13 shows a matrix showing the normalized score (0 to 1) for every scenario across all criteria. This heatmap allows decision-makers to spot specific strengths/weaknesses at a glance. For example, S4 (Non-Aerated Gravel Solar) is the only scenario without a "red" (poor) performance in any category, suggesting it is the most robust/balanced option. On the other hand, S1 (aerated cork solar) is deep green for Nitrate and GHG efficiency, but at the same time cork scenarios are deep red for COD removal due to the leaching effect from cork.

Figure 14 compares how the ranking of scenarios changes depending on what the user prioritizes (Balanced, Environmental, or Performance).

- **Balanced View**: S1 (Aerated Cork Solar) ranks 1st.
- **Environmental Priority**: If the goal is strictly minimizing Energy/GHG, S3 (Non-Aerated Cork Solar) moves to 1st place.
- **Performance Priority**: If water quality is paramount, S1 retains the top spot due to the high weighting of Nitrogen removal.

> **Key Insight:** There is no single "best" scenario; the optimal choice depends on whether the project prioritizes decarbonization (choose S3) or eutrophication control (choose S1).

The analysis of eight wetland-treatment configurations at the Codorníu site demonstrates **clear trade-offs between environmental performance, treatment effectiveness, and energy-GHG intensity**. Results show that the **Air_Cork Solar (S1)** configuration achieves the highest overall Nexus performance, providing the strongest combination of treatment efficiency, moderate energy use, and low emissions due to solar power. This scenario ranks first under both *balanced* and *performance-focused* MCDA criteria, making it the recommended option when water quality improvement and robust environmental performance are jointly required.

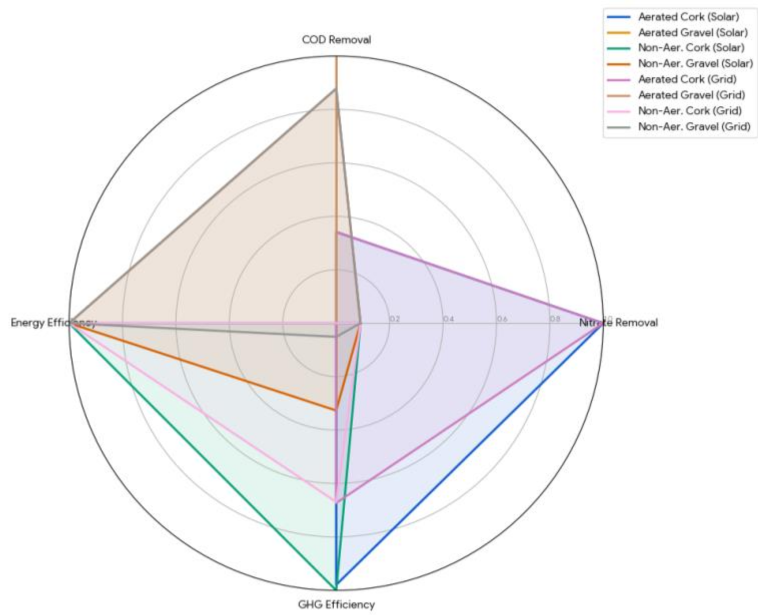

FIGURE 12. FINAL NEXUS DASHBOARD IN CODORNIU WITH NORMALIZED PERFORMANCE

If the priority is to **minimize energy use and carbon emissions**, the **No-Air Cork Solar (S3)** system is the most sustainable alternative. This scenario outperforms all others under the environment-priority MCDA scheme, delivering the lowest energy and GHG profile while maintaining moderate treatment efficiency. Conversely, systems relying on gravel substrates or grid electricity—particularly **S2, S6, and S8**—consistently show lower rankings due to weaker purification performance and/or higher carbon intensity, and they offer limited added value to the Nexus.

Overall, policymakers should prioritize **cork-based wetlands powered by solar energy**, which deliver both environmental and water-quality co-benefits. Aerated systems should be chosen when **maximum treatment performance** is essential, while non-aerated systems are preferable when **energy savings and emissions reduction** are the priority. The MCDA framework developed here enables transparent, data-driven decision-making and supports integrated planning aligned with WEFE Nexus principles.

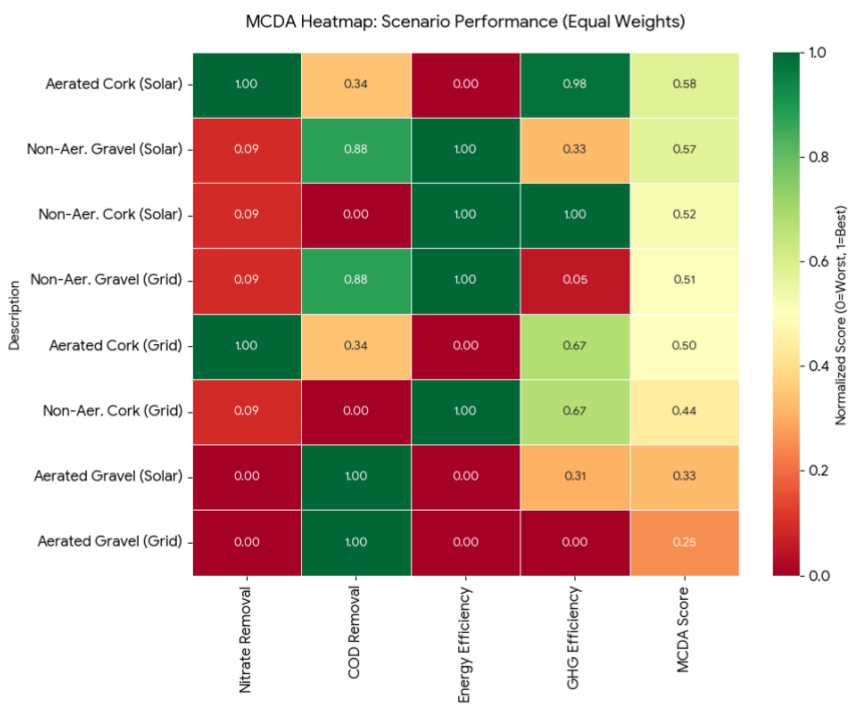

FIGURE 13. MCDA HEATMAP: SCENARIO PERFORMANCE FOR EQUAL WEIGHTS.

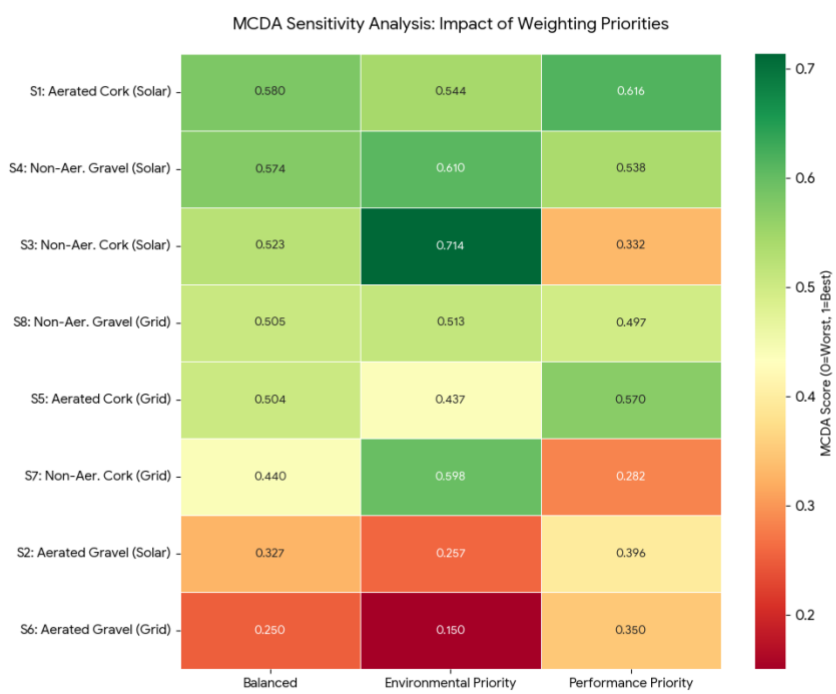

FIGURE 14. MCDA HEATMAP: SCENARIO PERFORMANCE FOR DIFFERENT WEIGHTS: A) BALANCED, B) ENVIRONMENTAL PRIORITY AND C) PERFORMANCE PRIORITY.

Together, Figures 12–14 provide a comprehensive assessment of how wetland design choices influence performance across the WEFE Nexus. Main lessons learned:

- **Cork consistently outperforms gravel**, validating circular-economy approaches.
- **Aeration is critical** for meeting high treatment targets, especially for COD.
- **Solar energy drastically reduces GHG emissions**, improving overall Nexus performance.
- MCDA and normalized indices reveal **robust agreement**: aerated cork systems are optimal when treatment is the priority; non-aerated cork is best when minimizing energy/GHG.
- The combined methodology (AI modelling + MCDA) provides a **transparent and traceable decision-support framework** for winery wastewater management and broader NbS implementation.

The analysis of Figures 12-14 confirms that Scenario 1 (Aerated Cork with Solar Energy) is the most effective Nexus solution, particularly for agricultural areas where Nitrogen pollution is a primary concern. It leverages the biological synergy of cork and aeration to maximize nutrient removal while using solar energy to mitigate the increased operational carbon footprint. Nevertheless, it should be emphasized that the leaching of organic matter from cork poses a limitation that necessitates management (e.g., a post-treatment polishing step).

3.4 AI WEFE Nexus Trade-Off Analysis

To analyse the multi-dimensional performance of the Codorníu scenarios, a **trade-off diferential map was generated using a Delta-Heatmap**. This visualization method highlights how each scenario performs relative to the average behaviour of the system across four **key WEFE Nexus indicators: energy consumption, greenhouse gas emissions (GHG), nitrate removal, and COD removal**. Rather than showing absolute values, the Delta-Heatmap displays deviations from the mean performance, enabling rapid identification of trade-offs, synergies, and dominant patterns.

The first step involves normalizing each indicator so that they become comparable across different scales and units. Performance indicators (nitrate and COD removal) are normalized directly, where higher values correspond to better performance. Conversely, **resource-consumption indicators (energy and GHG) are normalized inversely so that lower consumption leads to higher normalized scores**, ensuring all metrics follow the same interpretation of “**higher = better Nexus performance**”.

Then, for each scenario, the normalized value is compared with the average across all scenarios, producing a delta value (Δ = scenario – mean). Positive deltas indicate above-average performance (shown in green), while negative deltas indicate below-average performance (yellow to red). This representation makes **trade-offs** explicitly visible.

Overall, this method offers a transparent and data-driven way to examine the interactions among water quality improvement, energy demand, and climate impacts. By visualizing departures from average behaviour, the **Delta-Heatmap supports informed decision-making**, enabling users to quickly identify high-performing solutions, contextual trade-offs, and scenarios to avoid. This makes it an effective tool for integrated WEFE Nexus assessment and for communicating complex multi-criteria results to policymakers, stakeholders, and non-technical audiences.

Figure 15 shows that aerated cork systems show strong positive deltas for nitrate removal but slight negative deltas in energy use, illustrating the treatment–energy trade-off typical of aerated wetlands. Non-aerated cork systems display the opposite pattern: strongly positive deltas for energy and GHG, but moderately negative deltas for pollutant removal efficiency. By contrast, gravel-based systems—especially under grid power—tend to accumulate negative deltas across several indicators, revealing their more constrained environmental performance. The Delta-Heatmap thus provides immediate insight into which scenarios deliver balanced WEFE benefits and which involve structural compromises.

Therefore, **cork-based wetland systems consistently outperform gravel alternatives in both treatment performance and environmental efficiency, highlighting their value as circular and climate-resilient solutions**. Aerated cork configurations deliver the strongest pollutant removal, while non-aerated cork systems minimize energy use and emissions, enabling policymakers to align technology choices with regulatory or sustainability priorities. In contrast, gravel-based systems—especially when powered by the grid—show negative trade-offs across most Nexus indicators and offer limited strategic value. Overall, the results support **prioritising solar-powered, cork-based nature-based solutions as the most effective and balanced option for sustainable winery wastewater treatment.**

FIGURE 15. DELTA-HEATMAP REPRESENTING THE TRADE-OFFS FOR EACH SCENARIO ON CODORNIU DS1A DEMOSITE.

POLICY RECOMMENDATIONS - Codorníu WEFE Nexus Analysis

I. **Prioritize cork-based wetland systems.**
They deliver consistently higher WEFE Nexus performance and align with circular-economy and sustainability objectives.

II. **Use aerated cork systems when high pollutant loads require maximum removal.**
These configurations best support water-quality regulatory compliance.

III. **Choose non-aerated cork systems when reducing energy use and GHG emissions is the priority.**
Ideal for low-carbon strategies, off-grid operation, or areas with energy constraints.

IV. **Avoid gravel-based and grid-powered systems for future investment.**
They exhibit weak overall performance and poor trade-off balance.

V. **Integrate solar energy into wetland operation wherever feasible.**
Solar systems significantly reduce GHG emissions and improve Nexus efficiency.