

Sustainable Infrastructure through Cognitive Decision-Making

Franco Maciariello^{1,2*}, Fabrizio Benelli³ and Claudio Salvadori¹

¹New Generations Sensors, Italy

²Marketing Area, Santa Maria la Fossa (CE) – Italy

³Zetta Software Tlc Shpk, Albania

*Corresponding Author

Franco Maciariello, New Generations Sensors, Italy.

Submitted: 2025, Nov 27; **Accepted:** 2025, Dec 30; **Published:** 2026, Jan 30

Citation: Maciariello, F., Benelli, F., Salvadori, C. (2026). Sustainable Infrastructure through Cognitive Decision-Making. *J Agri Horti Res*, 9(1), 01-09.

Abstract

Rural infrastructures face a structural transformation driven by climate pressure, technological acceleration and the need to preserve environmental resources while meeting increasing agricultural demands. Water networks, energy distribution, agricultural logistics, land-use planning and territorial coordination have traditionally been managed through deterministic and rule-based approaches centred on human supervision and sectorial policies. Yet the rise of distributed sensing, data-rich agricultural ecosystems, explainable Artificial Intelligence and human-machine cognitive collaboration introduces a new paradigm in which decisions regarding water allocation, irrigation patterns, energy consumption, soil management and logistics coordination are no longer isolated operational choices, but components of a continuous cognitive cycle. In this evolving context, cognitive decision-making represents the structural capability to integrate human judgement with AI-supported analysis, dynamic feedback and explainable reasoning in order to improve sustainability outcomes and resilience performance. This article elaborates an integrated view of sustainable rural infrastructure as a human-centred cognitive system capable of absorbing unexpected climatic variability, dealing with resource scarcity, orchestrating agro-energy systems, ensuring transparent and resilient operations, and supporting long-term agricultural development. The conceptual framework emphasises three core dimensions: cognitive infrastructure design, explainable intelligence embedded in water and energy operations, and collaborative decision practices between human expertise and machine reasoning. The article develops an extensive business-oriented background, proposes a cognitive methodology for decision-making, and presents two business data tables and one conceptual cognitive-cycle graph.

Keywords: Sustainable Infrastructure, Cognitive Decision, Agriculture, Resilience, Human-Ai Collaboration, Rural Ecosystems, Water Management, Energy Integration

Abbreviations

AI – Artificial Intelligence

BCG – Boston Consulting Group

CGIAR – Consultative Group on International Agricultural Research

DER – Distributed Energy Resources

DSO – Distribution System Operator

ENISA – European Union Agency for Cybersecurity

EU – European Union

FAO – Food and Agriculture Organization of the United Nations

Human-AI – Human-Artificial Intelligence Collaboration

IEEE – Institute of Electrical and Electronics Engineers

IFAD – International Fund for Agricultural Development

IEA – International Energy Agency

ING-IND/35 – Ingegneria Economico-Gestionale (Industrial and Management Engineering)

IoT – Internet of Things

IPCC – Intergovernmental Panel on Climate Change

JAHR – Journal of Agriculture & Horticulture Research

OECD – Organisation for Economic Co-operation and Development

TSO – Transmission System Operator

UNCTAD – United Nations Conference on Trade and Development

WHO – World Health Organization

1. Introduction

Why Sustainable Rural Infrastructure Demands Cognitive Transformation

Over the past decade, agriculture has entered a phase of profound transition accelerated by climate change, resource scarcity, soil degradation, population dynamics, energy volatility and geopolitical uncertainty. Water scarcity increasingly affects irrigation systems in regions once considered stable, while progressive electrification of pumping infrastructure and agricultural logistics introduces new dependence on distributed energy grids. Simultaneously, precision agriculture and smart farming require real-time decision-making capabilities, shifting from seasonal planning toward continuous monitoring and adaptation. Reports from FAO and international agencies indicate that annual agricultural water consumption already constitutes around 70% of global withdrawals, a figure expected to increase under global warming scenarios if structural irrigation efficiency does not improve and if agricultural decision-making remains primarily reactive and rule-based. The agricultural sector is no longer dealing with predictable patterns of rainfall, soil moisture or groundwater recharge. Rather, it faces dynamic, uncertain, and geographically heterogeneous conditions that require flexible and adaptive infrastructure coordination [1-3].

Traditional infrastructures—irrigation canals, pumping stations, reservoirs, pipelines, rural distribution networks, logistic hubs—were conceived and dimensioned for a world that assumed climatic stability, centralised control, and limited data availability [4]. Today, that assumption is fragile. As global research makes increasingly evident, risks now arise from multi-dimensional uncertainty: seasonal unpredictability, extreme weather events, prolonged drought, soil erosion, freshwater salinisation, and the cascading effects of energy shortages on irrigation availability. Within this complex environment, sustainability cannot be reduced to energy efficiency or water saving. It must reflect the interdependence between infrastructure components, environmental variables, agricultural practices, socio-economic constraints and regulatory directives. Hence, the need to reimagine rural infrastructures as cognitive and resilient systems capable of sensing environmental conditions, analysing alternative options, involving domain experts, and executing sustainable decisions through interactive human–AI loops.

Importantly, cognitive decision-making does not imply replacing agronomists, water engineers or territorial planners with algorithms. Nor does it assume a deterministic view in which artificial intelligence automatically identifies the optimal strategy. Instead, cognitive infrastructure places human actors at the centre, reinforcing the role of expertise, local knowledge and contextual judgement. At the same time, AI supports decision processes through distributed sensing, explainable recommendations, risk analysis, and scenario simulation. This article adopts this perspective by framing sustainable infrastructure through the lens of cognitive decision-making, emphasising that resilience in agriculture requires a continuous alignment between human

judgement and AI-supported reasoning [5]. Such alignment transforms operational decisions—where to irrigate, when to irrigate, how much energy to allocate, how to adjust logistics under extreme weather—into systemic actions capable of reducing resource waste, improving crop performance and increasing territorial sustainability.

2. Background – Rural Infrastructures, Water, Energy and Agricultural Resilience

From an industrial-management viewpoint, rural infrastructures can be interpreted as distributed socio-technical systems composed of physical assets, data networks, regulatory constraints, agricultural processes and territorial governance. The traditional classification—water, energy and land-use systems—fails to capture the hybrid nature of modern rural infrastructure, which increasingly involves interconnected flows where water decisions influence energy demands, logistics choices affect water efficiency, and energy availability shapes irrigation timing. Irrigation networks represent the most critical component for agricultural regions subject to seasonal droughts or long-term scarcity. Irrigation channels, pumping stations, groundwater wells, reservoirs and distribution canals are operated by complex water authorities, consortia, irrigation districts and farming cooperatives. When droughts become more frequent, water allocation decisions become strategic rather than operational [6].

The sustainability of water systems depends not only on technological modernisation but also on decision processes that evaluate environmental conditions, weather expectations, soil characteristics and crop requirements. Conventional decision-making, based on historical averages and regulatory schedules, is poorly suited to the volatile hydrological regimes that FAO reports increasingly emphasise. Energy infrastructures in agriculture historically served limited functions: powering irrigation pumps, supporting warehouse operations, enabling basic logistics, and occasionally heating greenhouses. Yet the electrification of agricultural processes, the adoption of remote sensing devices, the use of electric vehicles in agricultural logistics, and the proliferation of digital farming tools significantly increase rural dependency on reliable and resilient energy systems. Renewable energy integration introduces opportunities for sustainability but also complexity—weather-dependent power generation, seasonal storage requirements, balancing between grid support and on-site solar production, and increasing vulnerability to energy price volatility [7,8].

At the strategic level, energy in agriculture is no longer an external input. It becomes part of the operational chain influencing irrigation decisions, logistic coordination, and territorial resilience. Hence the relevance of cognitive decision-making capable of integrating energy variability within irrigation and land management. Agricultural logistics is traditionally viewed as the downstream segment of production (storage, transportation, distribution). Yet logistics increasingly influences sustainability, particularly under extreme weather conditions, which may alter transportation efficiency, generate infrastructure disruption or require re-routing

flows of agricultural commodities. Cognitive decision-making in logistics involves proactive risk analysis, real-time environmental monitoring and scenario evaluation, prioritising sustainability outcomes [9].

By connecting these infrastructures—water, energy, logistics—into a systemic structure, agriculture becomes a cognitive infrastructure domain [10,11]. The concept is not merely technological; it reflects the integrated nature of rural operations, where decisions in one subsystem dynamically influence others. Reports from digital farming initiatives indicate that integrating irrigation and energy data can reduce water waste by more than 15% in specific contexts while reducing energy consumption through synchronised pumping schedules. Agricultural resilience denotes the capability of systems to absorb disturbances, adapt to climatic variability and recover after extreme events while maintaining productive equilibrium. In engineering-management research, resilience is interpreted through dimensions such as redundancy, flexibility, predictability, recoverability and learning. From a sustainable-infrastructure standpoint, resilience requires continuous feedback, adaptive control, multi-criteria decision analysis, and integration between human judgement and technological assistance.

Traditional agricultural management relies on deterministic rules: irrigation frequency determined by crop type, pumping hours regulated by water consortia schedules, seasonal planning based on historical averages. However, under climate uncertainty, rule-based processes become risk amplifiers rather than risk mitigators. Resilience demands dynamic decision-making supported by data, analytics and explainable recommendations that reflect complex environmental conditions. Human-AI collaboration is particularly relevant here: humans identify contextual risks, ethical concerns and territorial priorities; AI supports analysis, scenario simulation and pattern recognition. Resilience emerges from the synthesis of human understanding and machine intelligence rather than their separation.

3. Toward a Cognitive Decision-Making Paradigm

Cognitive decision-making represents a conceptual shift, moving from deterministic procedures toward dynamic, explainable and interactive processes. It leverages data, sensing and analytics while preserving human stewardship [12]. In rural infrastructure contexts, cognitive decisions involve identifying environmental risks such as drought, energy cost peaks, and soil salinity; analysing data from sensors, satellites, climatic models and logistics systems; evaluating sustainability outcomes including water saving, carbon impact, and soil conservation; combining machine recommendations and human judgement; adopting transparent execution procedures; and integrating continuous learning from feedback. Although artificial intelligence provides analytical support, human expertise remains central. Agronomists, irrigation engineers, water authorities and local operators validate the plausibility of recommendations, adjust constraints, evaluate externalities and ensure social and territorial acceptability.

Cognitive decision-making differs from automation. Automation executes pre-programmed logic, whereas cognitive infrastructure deals with uncertain, evolving and ambiguous conditions. Sustainable rural infrastructure cannot rely solely on deterministic optimisation. It requires cognitive reasoning capable of making sense of complex socio-ecological systems. In the emerging Human-AI paradigm, engineers, agronomists, data scientists and territorial planners collaborate around shared visibility of infrastructure conditions [13,14]. Explainability is essential: black-box models would undermine trust, accountability and compliance with environmental regulation. Decision-makers need to understand why AI suggests reducing irrigation in specific regions or postponing pumping activity until renewable energy availability increases.

A cognitive system must therefore make its reasoning interpretable, linking environmental sensing to recommendation logic and clearly discussing uncertainties. For instance, drought-prediction models used by water authorities increasingly integrate satellite-based soil moisture data, meteorological projections and hydrological models to recommend irrigation quotas. However, such models must explain the assumptions behind their suggestions, especially when water restrictions may affect crop yields or local livelihoods. This continuous collaboration between expert reasoning and AI-supported analysis becomes essential for territorial legitimacy and resilience outcomes.

4. Business Methodology and Cognitive Framework for Sustainable Rural Infrastructure

The methodology proposed in this article aligns with managerial-consultancy reasoning rather than experimental procedures. It structures cognitive decision-making across four macro-dimensions essential for sustainable rural infrastructures. First, data and sensing integration encompasses environmental, operational and infrastructural datasets from distributed sources including IoT devices, satellite monitoring systems, and hydrological models. Second, governance and stakeholder coordination involve collective decision-making processes across authorities, farming communities, consortia and territorial institutions. Third, risk and sustainability assessment identify environmental risks, sustainability impacts, resource availability and socio-territorial constraints. Fourth, explainable Human-AI collaboration integrates human expertise with explainable AI recommendations capable of supporting resilient decisions.

This methodology does not prescribe mathematical optimisation models. Instead, it provides a business-organisational structure for adopting cognitive systems in rural infrastructure while respecting the socio-ecological complexity of agricultural territories. In particular, the model emphasises that decisions must remain human-centric even when AI offers powerful analytical capabilities. The conceptual methodology requires a natural deepening of elements that connect sustainable infrastructure to actionable decision processes. In real agricultural territories, sustainability cannot be guaranteed unless the entire ecosystem of rural infrastructure is mapped against environmental vulnerabilities, energy constraints,

climatic uncertainty and socio-territorial implications. To make this multi-dimensional ecosystem tractable for decision-making, cognitive reasoning must be articulated into operational structures capable of supporting technicians, engineers, water consortia and agricultural managers in day-to-day decisions as well as long-term infrastructural planning [15,16].

One of the essential characteristics of cognitive decision-making is that the environmental context is not treated as a background variable but as a direct driver for infrastructural operation. Under severe climatic variability, every component of rural infrastructure—canal networks, pumping structures, pipelines, storage basins, micro-grids, renewable systems, feeder stations, agricultural roads, logistics hubs—becomes part of a dynamic configuration that must be manipulated according to real-time constraints and sustainability priorities. This is why the following analysis first introduces a structured view of rural infrastructures and related risks, and then moves to illustrate how cognitive

Human-AI collaboration can address such vulnerabilities through distributed decision logic.

The first analytical step consists in mapping the main rural infrastructure domains and explicitly connecting them to environmental, operational, climatic and territorial risks. The reason for this mapping is strategic: most rural territories still treat irrigation, energy and logistics as separate categories, leading to fragmented decision-making and sub-optimal sustainability outcomes. The following table translates real infrastructures into cognitive decision spaces. It is not intended to be exhaustive, but it highlights core infrastructures relevant for agricultural sustainability, resource efficiency, resilience and carbon-environmental objectives. FAO, European water-policy documentation and multiple smart-agriculture reports consistently emphasise the necessity of moving from technical asset classification to decision-oriented infrastructure mapping [17].

Rural Infrastructure Domain	Operational Role in Agriculture	Main Vulnerabilities	Environmental & Sustainability Risk	Structural Pressures & Uncertainties
Irrigation networks (surface, pressurised, drip)	Enable water allocation across fields and crops	Drought sensitivity, groundwater decline, salinisation	Over-extraction, soil degradation, water scarcity	Climate variability, regulatory restrictions
Pumping stations & water lifting assets	Support irrigation flows and water transfer	Energy cost dependency, failure under extreme heat	Carbon footprint, water–energy inefficiencies	Energy price volatility, seasonal peaks
Reservoirs & storage basins	Seasonal water reserve; flood & drought buffer	Evaporation losses, sedimentation	Resource depletion, ecological impact	Heatwaves, precipitation anomalies
Rural energy distribution (micro-grids, feeders)	Enable pumping, smart devices, electric logistics	Weather-dependent energy supply (renewables)	Reliability issues, carbon substitution uncertainty	Energy instability, grid constraints
Agricultural logistics (roads, hubs, storage)	Enable product movement and supply access	Infrastructure deterioration under extreme weather	Transport emissions, spoilage	Floods, storms, temperature extremes

Table 1: Key Rural Infrastructures and their Risk Profile

The table clearly reinforces how rural infrastructures are not independent entities but interconnected systems whose operations, vulnerabilities and sustainability risks must be evaluated simultaneously. For instance, pumping stations have historically been evaluated primarily from an energy-efficiency standpoint; yet under cognitive infrastructure reasoning they become water–energy nodes whose reliability deeply influences irrigation windows, crop health and soil sustainability. Similarly, reservoirs are no longer passive elements of water storage but active components of territorial resilience. Their operational parameters—evaporation, sedimentation, storage cycles—are directly affected by climatic variability and determine potential irrigation scheduling, energy intensity and agriculture-water balance. Finally, rural energy distribution, including micro-grids and renewable feeders, emerges not simply as an external utility but as a structural factor in sustainable irrigation scheduling and sensor-based agriculture. When coupled with decentralised renewables, energy infrastructures become dynamic and require

cognitive orchestration to reduce carbon emissions while enabling irrigation efficiency.

5. Insights and Evidence – Cognitive Human-AI Decision Examples for Sustainable Agriculture

Having established the risk profile and vulnerability patterns, the next step in the methodology is to show how typical decisions can be reframed through Human-AI collaboration. The following table exemplifies how explainable cognitive logic can support sustainability outcomes. This table is deliberately structured not as a technical optimisation model but as a decision-support instrument, illustrating practical cases that may be encountered by agricultural managers, water consortia or rural authorities. These cognitive decisions integrate multiple dimensions of rural infrastructure management, demonstrating how environmental sensing, human expertise and explainable AI recommendations converge to produce resilient and sustainable agricultural operations [18].

Cognitive Decision Domain	Type of Human-AI Decision	Intended Sustainability Benefit	Operational Effect	Resilience Contribution
Water allocation under drought	Adaptive irrigation scheduling based on soil moisture + expert validation	Reduced water withdrawal	Dynamic irrigation windows	Lower drought vulnerability
Pumping under energy constraints	Shift pumping to renewable-availability windows	Reduced carbon footprint	Lower peak-hour energy cost	Increased system stability
Reservoir management	AI suggests optimal storage based on forecast + human review	Preservation of reserve volume	Avoid early depletion	Strategic drought buffering
Agricultural logistics rerouting	Environmental risk-aware routing under extreme weather	Emission reduction	Adaptive transport routes	Mobility under climatic stress
Soil salinity control	AI identifies salinity risk zones + agronomist validation	Soil protection	Targeted irrigation	Long-term soil resilience

Table 2: Examples of Cognitive Human-Ai Decisions for Sustainable Infrastructures

Several implications emerge from this cognitive decision framework. First, Human-AI decision-making must remain transparent and interpretable: agronomists need to understand why irrigation should be postponed or reduced, and which datasets, climatic models or hydrological indicators support such suggestions [19]. In this sense, explainability is not a technical feature but a business requirement to ensure accountability, regulatory compliance and social acceptability. Second, sustainability here is not an abstract goal but the outcome of concrete decisions: when to irrigate, which pump to activate, whether to shift operations to different hours, how to preserve reservoirs, and where logistics must adapt to climatic conditions. These are exactly the points where traditional infrastructure management lacks flexibility and where cognitive supervision provides real added value.

Finally, resilience is recognised not as a static design attribute but as a continuous ability to adapt under climatic uncertainty, energy volatility and operational disruptions. This reflects modern resilience frameworks promoted by international agricultural agencies. The adoption of cognitive decision-making in agriculture has already shown impactful outcomes in enterprise-level smart farming programs, especially when drought, hydrological stress,

soil degradation or water scarcity pose structural risks [20]. Practical evidence across multiple FAO digital-farming initiatives demonstrates that AI-supported irrigation decisions, validated by expert agronomists, can reduce water withdrawal substantially, particularly in Mediterranean and arid regions. Similarly, energy scheduling driven by cognitive insights can reduce operational emissions by synchronising pumping activities with renewable availability or lower-carbon energy sources.

A cognitive rural-infrastructure system requires continuous sensing, reasoning, decision, validation and feedback. The following conceptual graphic illustrates this process in a managerial style suitable for ING-IND/35 orientation rather than academic modelling. It represents the iterative cognitive loop that integrates environmental monitoring, data interpretation, explainable recommendations, human validation, operational execution and continuous learning. This cycle emphasises that cognition within rural infrastructure is not algorithmic prediction followed by passive execution, but rather a continuous iterative process in which field operations generate new data, which then feed analytics and inform subsequent decisions.

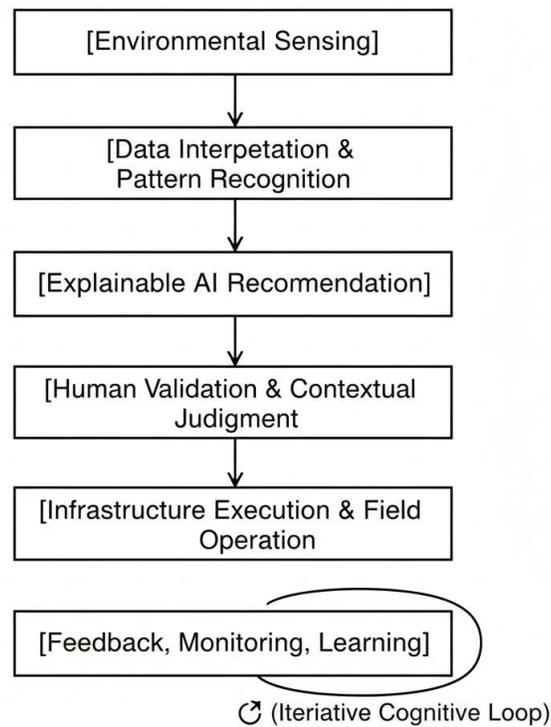


Figure 1: Conceptual Business Graphic of the Cognitive Decision Cycle for Sustainable Rural Infrastructure

The diagram emphasises that cognition within rural infrastructure is not algorithmic prediction followed by passive execution. Instead, it requires a continuous iterative cycle in which field operations generate new data, which then feed analytics and inform subsequent decisions. The cognitive loop therefore combines human interpretation and machine-supported reasoning. A crucial implication is that resilience is never fully achieved: it is continuously maintained. Furthermore, feedback is essential not only for technical calibration but for socio-territorial consensus. Water authorities, rural communities and agricultural stakeholders must understand how decisions are made and how uncertainty is handled. This demand for explainability goes beyond transparency; it shapes trust, legitimacy and long-term sustainability adoption. Under extreme climate scenarios—prolonged drought, severe rainfall deficits, extreme temperatures—it becomes essential to coordinate water storage, irrigation scheduling, energy brousing and transportation planning as integrated decisions rather than isolated functions.

6. Managerial and Societal Implications of Cognitive Rural Infrastructures

The shift toward cognitive decision-making within rural infrastructures generates a profound transformation across agriculture, energy–water governance and territorial sustainability. At managerial level, organisations must recognise that sustainability and resilience are not static infrastructure attributes, but dynamic capabilities requiring permanent alignment between human reasoning, data-driven analysis and explainable Artificial Intelligence. This fundamental reorientation requires new

competencies, institutional frameworks, governance mechanisms and organisational models that allow cognitive decision processes to operate reliably under climatic uncertainty. Within traditional infrastructure management, decisions were primarily centralised, deterministic and planned through linear regulatory schedules aligned to seasonal patterns. Contemporary agriculture, however, operates under dynamic and uncertain conditions, where water availability may drastically fluctuate, energy prices may rise unpredictably and extreme climatic events may disrupt logistics and territorial access [21].

In this context, managerial functions must evolve, adopting new roles of mediation between technical layers, environmental variability and socio-economic priorities. The central managerial implication is that decision processes themselves become part of the infrastructure. The cognitive dimension transforms classic assets—canals, pumps, reservoirs, micro-grids—into adaptive and interconnected nodes whose behaviour must be continuously orchestrated. Cognitive infrastructures are not defined by technology alone; they are organisational systems rooted in human knowledge, environmental awareness and adaptive governance. From a human-capital standpoint, agricultural enterprises and water-energy authorities will increasingly require hybrid professional figures, capable of understanding agronomy, infrastructure engineering, energy management and data-driven reasoning [22,23]. These new profiles will shape cognitive-operational decisions, validating machine suggestions, assessing contextual implications and ensuring territorial coherence.

Cognitive infrastructures introduce new managerial responsibilities. The question is not whether AI should support decisions, but how humans should supervise, validate and co-create decisions with AI [24]. Human-AI collaboration entails active engagement in the decision cycle, not passive acceptance of algorithmic outcomes. Managers must be able to interpret analytics, understand model assumptions, evaluate environmental risks and guide the integration of machine reasoning into territorial infrastructure strategies. Explainability thus becomes a managerial requirement, ensuring transparency and accountability, especially when sustainability decisions affect multiple stakeholders. For example, if irrigation restrictions are recommended in a region experiencing severe drought, legitimate questions must be raised regarding fairness, crop selection, local economic conditions and long-term soil protection. Human experts must remain responsible for aligning decisions with agronomic knowledge and territorial norms.

Cognitive infrastructures require governance architectures that integrate diverse institutional actors: water consortia, energy providers, local authorities, agronomic institutions, territorial agencies and environmental departments. Cognitive decision-making must satisfy the multiple requirements of these actors while ensuring sustainable outcomes. Given the cross-sectoral nature of cognitive decisions, institutional fragmentation represents a structural challenge. Territorial governance must evolve, adopting collaborative mechanisms that support distributed decision processes while maintaining the legitimacy of local authorities [25,26]. The involvement of farmers, cooperatives and communities becomes crucial, particularly where social acceptance shapes infrastructure feasibility. In regions with strong agricultural identity, cognitive decisions must respect territorial heritage and local agronomic practices, acknowledging that sustainability cannot be imposed solely through data or algorithms.

Sustainable infrastructure requires fair allocation of resources. Under drought or extreme weather, cognitive decisions must incorporate equity criteria ensuring that resource limitations do not disproportionately affect vulnerable regions or small agricultural communities. Human validation again plays a crucial role, ensuring that AI-supported decisions remain socially acceptable and ethically grounded. From a societal viewpoint, cognitive infrastructures can enhance food security, water availability and energy sustainability while reducing emissions and territorial vulnerability. Yet without proper governance, cognitive decisions may create new inequalities. Therefore, the societal transition requires institutional commitment to transparency, fairness and long-term territorial resilience. Cognitive infrastructures generate a duty of care: those designing, operating and validating cognitive systems must assume responsibility for environmental outcomes. Technologies are tools, but sustainability outcomes depend on human stewardship [27-29].

For agricultural leaders, the emergence of cognitive infrastructures demands strategic and cultural transformation. Traditional management, based on individual expertise and sector-specific

decision frameworks, must be replaced by systemic reasoning capable of integrating environmental uncertainty, technological complexity and organisational innovation. Leadership is therefore measured not only through operational efficiency, but through the ability to foster collaboration, build human-AI competencies and orchestrate cognitive infrastructure models across complex ecosystems. This transformation implies that executive roles evolve from operational supervision toward strategic facilitation of human-machine collaboration. Leadership will increasingly involve mediating between engineering constraints, agronomic needs, environmental regulations and socio-economic objectives. Strategic decision-making must therefore incorporate long-term sustainability outcomes, evaluating trade-offs between short-term productivity and long-term ecological preservation.

7. Consulting Pill – Executive Takeaways for Decision-Makers

The core consultancy insight is that sustainable rural infrastructures depend on the capacity to integrate human expertise with explainable decision systems. Cognitive infrastructures are not created by implementing AI solutions alone; they emerge when organisations build a holistic decision environment that unites environmental sensing, human expertise, technological systems and adaptive governance. Executives should adopt a cognitive infrastructure mindset, viewing infrastructure as a living system rather than a static asset base. This perspective enables continuous adaptation under climate variability, technological evolution and market pressure. Furthermore, decision-makers should promote human-AI integration that respects agronomic knowledge, cultural heritage and social equity. Sustainability outcomes depend on human validation, contextual insight and territorial responsibility. In this regard, cognitive systems must be fully explainable, ethically grounded and contextually relevant.

Practical executive takeaways revolve around four strategic pillars. First, adopting explainable AI ensures that decision-makers understand the reasoning behind machine recommendations and can validate them against agronomic knowledge and territorial constraints. Second, elevating human expertise recognises that cognitive systems amplify rather than replace human intelligence, requiring investment in professional development and hybrid competencies. Third, investing in data and sensing infrastructures creates the foundational layer for cognitive decision-making, enabling real-time environmental monitoring and predictive analytics. Fourth, embracing cognitive governance models establishes institutional frameworks that support collaborative decision processes across multiple stakeholders, ensuring transparency, fairness and long-term sustainability. While these takeaways do not constitute prescriptive action points, they provide managerial orientation towards sustainable infrastructure development, supporting agricultural resilience and long-term competitiveness.

8. Conclusions and Future Directions

Cognitive decision-making represents a structural transformation of sustainable rural infrastructures. Through human-AI collaboration, agriculture can address climate variability, energy

uncertainty, water scarcity and territorial vulnerability with adaptive and resilient strategies. Rather than replacing human expertise, cognitive infrastructures empower experts with richer information, analytical capabilities and explainable reasoning. Sustainable rural infrastructure emerges when cognitive decision processes are integrated across irrigation systems, reservoirs, pumping assets, renewable energy networks and agricultural logistics. Cognitive reasoning reshapes these infrastructures as interconnected systems capable of continuous adaptation, learning and environmental stewardship.

The future of agriculture will therefore be determined by the capacity to combine technological capability with human contextual intelligence. Sustainable rural infrastructures require holistic decision ecosystems grounded in ethical awareness, social fairness and environmental responsibility. Cognitive infrastructures offer an opportunity to build resilient agricultural territories capable of facing climatic uncertainty while preserving ecological integrity and supporting economic development. Future research and implementation efforts should focus on developing standardised frameworks for cognitive decision-making, establishing governance models that balance efficiency with equity, and creating educational programs that prepare agricultural professionals for human-AI collaboration. Additionally, regulatory frameworks must evolve to support explainable AI adoption while ensuring environmental protection and social justice.

Ultimately, the transition toward cognitive rural infrastructures represents not merely a technological evolution but a fundamental reimagining of how agricultural systems relate to environmental resources, energy systems and human communities. By embracing cognitive decision-making as a strategic imperative rather than a technical option, agricultural organisations can build the resilient, sustainable and equitable infrastructures necessary for long-term territorial prosperity and environmental stewardship. The path forward requires commitment, investment and collaboration across multiple domains, but the potential rewards—enhanced resilience, improved sustainability and strengthened food security—justify the transformative effort required.

References

1. IPCC (2023). Climate change impacts on agriculture and adaptive capacity assessment. Intergovernmental Panel on Climate Change. <https://www.ipcc.ch>
2. European Commission (2023). Digital agriculture and smart farming strategies for climate adaptation. EU Agricultural Policy Directorate. <https://ec.europa.eu/agriculture>
3. FAO (2023). Water scarcity and agricultural sustainability: Global assessment and regional perspectives. Food and Agriculture Organization of the United Nations. <https://www.fao.org/water>
4. IFAD (2023). International sustainable rural infrastructure initiatives and digital farming programs. International Fund for Agricultural Development. <https://www.ifad.org>
5. Benelli, F., Maciariello, F., & Salvadori, C. (2024). The influence of technologies on organizational culture in innovative SMEs.
6. OECD (2023). Agricultural water management policies and sustainability frameworks. Organisation for Economic Co-operation and Development. <https://www.oecd.org/agriculture>
7. European Environment Agency (2023). Water stress and agricultural sustainability in Europe. <https://www.eea.europa.eu>
8. IEA (2023). Energy in agriculture: Electrification trends and renewable integration. International Energy Agency. <https://www.iea.org>
9. UN Water (2023). Integrated water resources management in agricultural territories. United Nations Water Programme. <https://www.unwater.org>
10. Benelli, F., Maciariello, F., Marku, R., & Stile, V. (2025). Towards an Energy Physical Internet: Open Business Models and Platforms for Electricity Distribution Enabled by IoT, Blockchain, and Conditional Payments. In *Conference Book of Abstracts of the 4th International Conference Creativity And Innovation In Digital Economy (CIDE 2025)*. Universitatea Petrol-Gaze (UPG).
11. Maciariello, F., Benelli, F., Sangiuolo, G., Lorenzi, E., Caponio, C., & Salvadori, C. (2025, September). TrackOne: Smart Logistics for a Sustainable and Interoperable Agricultural Supply Chain in the Era of Digitization. In *2025 International Conference on Software, Telecommunications and Computer Networks (SoftCOM)* (pp. 1-7). IEEE.
12. Deloitte (2023). Cognitive infrastructure for sustainable food systems. Deloitte Insights. <https://www2.deloitte.com>
13. Nature Sustainability (2023). Cognitive decision systems for agricultural water management under climate uncertainty. Nature Publishing Group.
14. IEEE (2023). Human-AI collaboration frameworks for critical infrastructure management. IEEE Technology and Society Magazine.
15. Benelli, F., Caronna, M., Kelliçi, E., & Maciariello, F. (2025). Leveraging the urban physical internet for sustainable heritage management: Edge AI, federated learning, and digital twins. In *HERITAGE CAPITALISATION AND DEVELOPMENT-IDENTITY, INNOVATION, DIGITALISATION, ENVIRONMENT, AWARENESS AND SECURITY" HERITAGE-IIDEAS*.
16. Gartner (2023). Top strategic technology trends for agriculture and food supply chains. Gartner Research.
17. FAO (2022). Smart irrigation programmes and water efficiency in Mediterranean agriculture. <https://www.fao.org/land-water/water>
18. BCG (2023). Precision agriculture and AI-enabled decision support systems. Boston Consulting Group.
19. Benelli, F., Kelliçi, E., Maciariello, F., & Stile, V. (2025). Artificial Intelligence for Decentralized Orchestration in the Physical Internet: Opportunities, Business Trade-offs, and Risks in Road Freight Logistics. In *Conference Book of Abstract of the 4th International Conference Creativity And Innovation In Digital Economy (CIDE 2025)*.
20. CGIAR (2023). Climate-resilient agriculture research and innovation platforms. Consultative Group on International

-
- Agricultural Research. <https://www.cgiar.org>
21. McKinsey & Company (2022). The future of agriculture: Digital transformation and sustainability. McKinsey Global Institute.
 22. Benelli, F., Maciariello, F., Salvadori, C., Kelliçi, E., & Stile, V. (2025). Human-AI Collaboration in SMEs: A Role-Sensitive Framework for Cognitive Enterprise Hubs. In *Proceedings of the 22nd Conference of the Italian Chapter of the Association for Information Systems (ITAIS 2025)*.
 23. UNCTAD (2023). Digital agriculture for sustainable development. United Nations Conference on Trade and Development. <https://unctad.org>
 24. Benelli, F., Maciariello, F., Salvadori, C., Kelliçi, E., & Stile, V. (2025). Human-AI Collaboration in SMEs: A Role-Sensitive Framework for Cognitive Enterprise Hubs.
 25. World Bank (2023). Climate-smart agriculture and rural resilience: Investment frameworks for developing regions. <https://www.worldbank.org/agriculture>
 26. Benelli, F., Kelliçi, E., Maciariello, F., Salvadori, C., & Stile, V. (2025). Enhance Student Wellbeing and Digital Literacy with Machine Learning and Spatial Analysis. In *The 2nd Workshop on Education for Artificial Intelligence (EDU4AI 2025)*.
 27. WHO (2023). Climate change, food security and public health: Integrated assessment frameworks. World Health Organization. <https://www.who.int>
 28. Liberti, F., Avolio, F., Cicoira, V., Cosmo, N., Laudonia, A., Maciariello, F., & Stile, V. (2025). Distributed Artificial Intelligence and Health Governance: A Multidimensional Analysis of the Tensions Between Rules, Ethics and Innovation.
 29. ENISA (2023). Cybersecurity for critical agricultural infrastructure. European Union Agency for Cybersecurity. <https://www.enisa.europa.eu>

Copyright: ©2026 Franco Maciariello, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.