Editorial

WM&R

Landfills as integrated water–energy–food–ecosystems Nexus hubs: A prospective vision for circular economy implementation

Waste Management & Research
2026, Vol. 44(1) 1–7

DOI: 10.1177/0734242X251399507
journals.sagepub.com/home/wmr
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The water–energy–food–ecosystems (WEFE) Nexus framework has gained increasing recognition as a holistic approach to address interconnected resources challenges. It explicitly acknowledges that interventions in one domain can generate cascading effects across others, while promoting resource efficiency and minimizing cross-sectoral inefficiencies (Del Borghi et al., 2020; González-Rosell et al., 2025; Nazir and Doni, 2024). Recent studies highlight that embedding waste management within the WEFE framework can unlock synergies that advance circular economy objectives and provide a coherent structure for addressing the interconnected challenges of waste management, water resources, energy demand, food production, and ecosystem health (Chaher et al., 2024; Segovia-Hernández et al., 2017). These benefits become particularly evident when bio-based resource recovery is coupled with energy and water reclaim (Del Borghi et al., 2020; Segovia-Hernández et al., 2017; Zorpas, 2024).

Traditionally regarded as passive waste repositories, landfills are now being reconceptualized as active resource hubs capable of delivering multiple WEFE-related outputs. Although several of the enabling technologies, such as landfill gas (LFG) upgrading, advanced landfill leachate (LL) treatment, renewable energy generation and innovative biomonitoring, have been successfully demonstrated individually, their systemic integration within a WEFE-oriented framework remains an emerging frontier. Such integration could offer substantial environmental and economic benefits, transforming landfills into platforms for sustainable resource recovery and cross-sectoral innovation. Building on scientific evidence and practical experiences, this editorial highlights how WEFE-oriented strategies can create synergies, reduce cross-sectoral inefficiencies and redefine the role of landfills within the circular economy.

Water: Advanced LL treatment

LL is a complex heavily polluted aqueous matrix formed through the percolation of rainwater and the biodegradation of organic matter within landfill cells (Liu et al., 2015; Naaz et al., 2025). It contains high concentrations of dissolved organic matter, heavy metals, inorganic salts (Ghosh et al., 2015; Moody and Townsend, 2017) and therefore requires advanced treatment to remove both conventional and emerging contaminants. Once considered solely a negative externality, LL is now increasingly recognized as a recoverable water resource when properly treated. Reverse osmosis membranes, particularly when operated in cascading configurations and preceded by suitable pretreatments, have demonstrated excellent contaminant rejection performance (Arsalan et al., 2025; Katakam and Bahadur, 2024), further reinforcing the feasibility of this technology as a robust and reliable technology for LL management. The permeate obtained through these systems can be reused in several on-site applications within the WEFE framework. Specifically, it can serve as a water source for moisture control via treated leachate recirculation, an approach designed to enhance LFG production and promote faster stabilization of landfilled waste by accelerating or reactivating the biodegradation of organic fractions (Bilgili et al., 2012). Field evidence supports these benefits: a pilot study conducted in Florida (USA) reported an increase in methane (CH_4) concentration in LFG from about 38% to 50% within 2 months of initiating the controlled recirculation of the effluent derived from LL treatment (Sanphoti et al., 2006). Hussein and Ibrahim (2023) further demonstrated that vertical-well recirculation systems effectively distribute both moisture and nutrients, enhancing methanogenic activity. However, recirculation practices must be supported by robust monitoring, environmental risk assessments, and regulatory oversight to prevent groundwater or soil contamination (Srivastava and Chakma, 2022). Moreover, a comprehensive sustainability assessment, encompassing environmental, economic and social dimensions, should guide implementation to ensure long-term viability (Naddeo et al., 2016; Reddy et al., 2022). Recent research emphasizes the importance of integrating a life-cycle assessment when designing LL recirculation or reuse strategies to ensure alignment with broader sustainability goals (Janga and Reddy, 2024). The residual effluent from advanced leachate treatment, if not recirculated, can also serve as a feedstock for green hydrogen (H_2) production via electrolysis powered by renewable energy. Site-specific demonstrations have confirmed the feasibility of this pathway, with treated LL permeate successfully employed in photovoltaic (PV)-powered electrolyzers to generate green H_2 (De Paola et al., 2025). Integrating this energy recovery pathway not only closes the landfill water loop but also embeds its operation within the water-energy nexus, transforming a former waste stream into a resource for sustainable energy generation.

Energy

Waste to energy: LFG collection and upgrading

LFG, typically consisting of 50–60% methane (CH_4) and 40–50% carbon dioxide (CO_2), contains elevated content of greenhouse gases (GHGs), which represent a negative externality but also a valuable source of recoverable energy carriers (Gupta et al., 2022; Scheutz et al., 2023). Modern LFG collection systems, integrated with continuous monitoring, can achieve high efficiencies in terms of collection rate, thereby mitigating fugitive emissions while enabling greater recovery of LFG for energy valorization. The feasibility of conventional LFG valorization via combined heat and power (CHP) cogeneration depends largely on the CH_4 concentration. When CH_4 levels drop below the typical threshold of 30–40% (U.S. Environmental Protection Agency, 2024), auxiliary fuels may be required to sustain stable engine operation. Moreover, the efficiency of CHP systems is constrained by the availability of a consistent local heat demand, such as for self-use or district heating for industrial processes, without which a substantial share of thermal energy remains unused, reducing overall efficiency and increasing GHG emissions. CHP systems often determine high pressures in terms of emissions into the atmosphere of priority gaseous pollutants, when proper technologies are not correctly implemented for exhausted gas emission treatment.

As an alternative, LFG can be upgraded to biomethane (bioCH_4) through technologies such as membrane separation, pressure swing adsorption (PSA) or chemical scrubbing. These processes can produce high-purity bio-CH_4 ($>95\%$ CH_4) suitable for on-site power generation, injection into natural gas grids, or liquefaction for heavy transport. However, grid injection requires either proximity to existing gas infrastructure or investment in dedicated pipelines, while liquefaction is economically viable only when sufficient demand exists in the transport sector, given the energy-intensive nature of the process (Hoo et al., 2018).

In all valorization scenarios, the availability of policy incentives and the potential for GHG reduction are decisive factors in determining the optimal valorization route (Catalano et al., 2024; Negro et al., 2025; Noussan et al., 2024).

On-site electricity generation from renewable energy sources

Closed and capped landfill surfaces provide suitable conditions for PV system installation. The Hickory Ridge Landfill (Conley, GA, USA), for instance, hosts more than 7000 thin-film PV panels directly adhered to an exposed geomembrane cap. The installation, with a capacity of 1 MWp, showcases how landfills can be effectively repurposed for clean energy generation, while simultaneously reducing GHG emissions and eliminating the need for conventional soil-cover maintenance. Flexible geomembrane-based PV systems further expand this potential by enabling installation on steep side slopes that would otherwise be unsuitable for any type of development. Such systems can increase power density by up to threefold compared with ballasted PV systems, thereby maximizing land-use efficiency (Szabó et al., 2017, Santos et al., 2025).

Hybrid energy configurations that combine PV systems with LFG utilization can enhance overall system efficiency and operational reliability. Lopes et al. (2019) demonstrated that PV-LFG hybrid systems optimize the temporal availability of electricity and reduce overall energy costs. To address the intermittency of solar generation, PV installations should be integrated with battery energy storage systems (BESS; Lo Franco et al., 2021; Bonilla and Le, 2023). BESS units store surplus electricity produced during peak solar hours and release it during periods of low generation, thereby stabilizing power supply. The stored energy can be used on-site to improve energy self-sufficiency or exported to the grid, depending on system configuration and local energy demand.

In addition, wind turbines installed along landfill perimeters or elevated zones can complement PV and LFG systems by providing additional renewable energy generation. However, their deployment must be preceded by comprehensive geotechnical and structural assessments, as the dynamic loads they generate may compromise landfill stability.

When appropriately designed and integrated, LFG valorization, renewable energy systems (PV and wind turbines) and BESS technologies can enable grid-independent landfill operation, strengthen energy resilience and advance circular economy and decarbonization objectives.

Green hydrogen valorization

Green H_2 can be generated at landfill sites either through the electrolysis of water recovered from LL treatment or via selective extraction from LFG. The recovered H_2 can act both as a clean energy carrier and as a feedstock for upgrading gaseous by-products. Among electrolysis technologies, proton exchange membrane and anion exchange membrane electrolyzers are particularly suited for decentralized landfill applications, owing to their operational flexibility, high current densities and compatibility with variable renewable energy sources (Mamlouk, 2022; Sebbahi et al., 2024). Solid oxide electrolysis cells (SOECs), while achieving superior efficiency in H_2 production, operate at high temperatures and require a steam supply, making them more appropriate for sites with opportunities for thermal integration (Lahrichi et al., 2024; Min et al., 2022).

The produced H_2 can serve not only as a renewable energy vector but also as a feedstock for upgrading gaseous streams. One promising route involves blending H_2 with bioCH_4 to generate hydrobiomethane, a hydrogen-methane mixture with higher energy density and improved combustion properties. Another emerging pathway is the biological or catalytic methanation of CO_2-rich streams, including off-gases from LFG upgrading units (e.g. PSA tail gases), or low-methane LFG from older landfill basins.

Catalytic methanation based on the Sabatier reaction ($CO_2+4H_2 \leftrightarrow CH_4+2H_2O$) remains one of the most established strategies for carbon dioxide (CO_2) valorization (Oliva et al., 2023). The reaction is highly exothermic ($\Delta H = -165$ kJ/mol), but achieving an acceptable conversion rate and selectivity is inherently challenging due to kinetic limitations at low temperatures, which require highly active catalysts to overcome the activation energy barrier. To balance thermodynamic and kinetic constraints, the reaction is typically carried out at temperatures of 200°C–400°C and pressures between 1 and 30 bar (Kim, 2025), using transition metal catalysts such as nickel or ruthenium to achieve high CO_2 conversions. Accurate control of temperature, pressure, and the CO_2/H_2 feed ratio is crucial to maximize CH_4 productivity and prevent undesired side reactions. Since the process is extremely temperature-sensitive, precise thermal management is essential to maintain catalyst stability, prevent sintering, and ensure high CH_4 selectivity (Cañada-Barcala et al., 2026; Italiano et al., 2025). To address these challenges, advanced reactor configurations adopt multistage reactors with intermediate cooling zones, oil or molten-salt-cooled multi-tubular reactors, or heat-exchanger-assisted reactors that enable effective heat recovery. The recovered thermal energy can be reused within the process, for instance, to preheat feed gases or supply steam to SOECs, thereby enhancing overall energy efficiency and contributing to plant self-sufficiency (Tripodi et al., 2020).

Biological methanation offers a low-energy and resilient alternative for CO_2 conversion, particularly well-suited to decentralized contexts and intermittent green H_2 availability. This process exploits hydrogenotrophic methanogenic archaea to convert CO_2 and H_2 into CH_4 under anaerobic, low-temperature conditions (Angelidaki et al., 2011; Thapa et al., 2023; Tsapekos et al., 2021). Compared with catalytic systems, biological methanation is more tolerant to gas impurities and more adaptable to fluctuating H_2 supplies. Pilot-scale studies have achieved bioCH_4 purities above 94% and H_2 utilization efficiencies up to 98% (Tsapekos et al., 2021).

Overall, the integration of green H_2 valorization pathways not only enables the production of renewable energy carriers but also mitigates CO_2 emissions, delivering substantial environmental and economic benefits for next-generation landfill management.

Food and ecosystems

Historically considered unusable, landfills in the post-closure phase are increasingly being repurposed for socially and environmentally beneficial uses, including their transformation into parks, recreational trails, and sports facilities. The feasibility of such redevelopment depends on several site-specific factors, such as landfill size, location, climatic conditions and the interests of local stakeholders. Notable examples of successful transformations include Ariel Sharon Park (Tel Aviv, Israel), Freshkills Park (New York, USA), Garraf Park (Barcelona, Spain) and San Giuliano Park (Venice, Italy), all illustrating how environmental restoration and landscape architecture can be effectively integrated to create multifunctional public spaces (Li and Liu, 2024).

Beyond recreational reuse, landfill valorization is increasingly extending into the agricultural and food production sectors, in alignment with the WEFE Nexus principles (Hard et al., 2019). An example is found at the ECCO Centre in Alberta (Canada), where managed apiaries installed on vegetated landfill caps produce nearly 200 kg of honey in a single season. Supported by wildflower plantings, these apiaries enhance pollinator health, promote local biodiversity and generate low-input, locally sourced food products. A pioneering initiative on a landfill site in Wiltshire is preparing to repurpose a waste-management facility into a year-round food production hub by integrating greenhouse cultivation with captured landfill emissions. The heat and cleaned CO_2 generated from biogas collection and treatment system is used to enrich greenhouse environments sited directly above landfill, creating a closed-loop system where waste-gas by-products drive the cultivation of fruits and vegetables, without any contact between crops and landfill.

Land and soil pollution potentially caused by landfilling have emerged as a major environmental concern due to their potentially detrimental ecological consequences. Heavy metals, although naturally present in soils at low concentrations, become pollutants when their levels rise as a result of anthropogenic activities (Gautam et al., 2024). These elements can impact soil health, which is typically assessed through a combination of physicochemical and biological indicators (Essienubong et al., 2018; Kooch et al., 2024). Among these, biological parameters are often prioritized, as soil biota play a fundamental role in nutrient cycling, organic matter decomposition and the maintenance of ecosystem stability, while also exhibiting high sensitivity to both natural and anthropogenic disturbances acting as sentinel for environmental pollution (Gautam et al., 2024; Gu et al., 2022). In contaminated soils, pollutants can markedly modify the structure and diversity of microbial and faunal assemblages, thereby altering key ecosystem functions (Zhang et al., 2021). In this context, biomonitoring represents an effective approach for evaluating environmental quality by observing the physiological and ecological responses of living organisms to pollution stress. Unlike conventional instrumental monitoring, which provides punctual and quantitative measurements, biomonitoring integrates the effects of multiple pollutants over time and reflects the real conditions as perceived by biological systems (Vaverková et al., 2025). The use of plants as bioindicators is particularly advantageous around landfills, as it allows for the early detection of deviations from typical conditions and the identification of ecological changes such as dominance shifts or loss of biodiversity. Through the continuous assessment of vegetation composition and vitality, biomonitoring can reveal long-term trends in ecosystem alteration and serve as an early warning system for potential environmental degradation (Paoli et al., 2012). For these reasons, incorporating plant-based biomonitoring would provide a complementary and ecologically meaningful tool to conventional monitoring networks, supporting adaptive management practices and the sustainable rehabilitation of landfill areas.

Honeybees (*Apis mellifera*) and their hive products, honey, wax and pollen also serve as highly effective biomonitors, passively accumulating environmental pollutants from air, soil and water across a foraging area of up to 10 km^2 (Conti et al., 2022; Cunningham et al., 2022; Mair et al., 2023). In their dual role as pollinators and environmental sentinels, honeybees provide valuable insights into the presence and dynamics of emerging contaminants, including heavy metals, organic pollutants, and microplastics (Fuente-Ballesteros et al., 2025). Recent findings by Fuente-Ballesteros et al. (2025) confirmed the presence of microplastics in honey, pollen and within bee tissues, specifically the gut and cuticle. These results underscore the suitability of honeybees and their products as non-invasive, integrative tools for environmental monitoring.

Systematic reviews and field studies further demonstrate that bees can provide detailed qualitative and quantitative data on trace elements (Pb, Cd, Cu, Zn, Cr and Ni), polycyclic aromatic hydrocarbons (PAHs) and particulate matter, often with greater spatial and temporal sensitivity than conventional stationary monitors (Cunningham et al., 2022; Mair et al., 2023; Skorbiłowicz and Skorbiłowicz, 2019). For example, Catalano et al. (2024) monitored hives near a waste-to-energy plant in Italy and detected fluctuations in dioxins, trace metals, PAHs and pesticides, including notable declines during the COVID-19 lockdown, which reduced anthropogenic emissions. Similarly, Ruschioni et al. (2013) demonstrated the effectiveness of honeybees as regional bio-monitors in a 3-year study across 10 nature reserves in central Italy, identifying spatial and temporal variations in heavy metals and pesticide residues. Additional studies have highlighted bees' selective bioaccumulation behaviour. Saunier et al. (2013) compared contamination levels in hive products with those in lichens and mosses near a historic mining site, finding that while lichens and mosses exhibited high heavy metal accumulation, hive products remained uncontaminated, indicating bees' natural filtering capacity and their reliability for long-term surveillance. Conti et al. (2022) further validated the use of honeybees and their products in atmospheric monitoring, identifying significant accumulation of traffic-related metals (Cu, Sn, Mn), biomass-burning markers (K, Rb, Cs, Li), and soil-derived elements (Al) in bees and their products (e.g. wax, pollen, and honey), thereby confirming bees as highly sensitive bioindicator.

In this context, biomonitoring on remediated landfill sites offers a unique synergy for ecosystem restoration.

Pathway towards WEFE integration: Prospective, opportunities and policy alignment

The WEFE Nexus framework mitigates intersectoral conflicts and enhances resource efficiency by promoting interventions that advance multiple sustainability goals simultaneously (Del Borghi et al., 2020; Nazir and Doni, 2024; Segovia-Hernández et al., 2017). Effective governance requires transparent performance monitoring, including key indicators such as CH_4 (or H_2) purity and recovery rates, water recovery efficiency, GHG emission reduction and biomonitors contaminant levels. These should be complemented by third-party audits and stakeholder engagement strategies, aligned with circular economy principles and broader sustainability governance frameworks (Brunner et al., 2023; Zorpas, 2024; Zorpas et al., 2025). It is also essential to implement advanced emission monitoring and control systems, including emerging artificial intelligence (AI)-driven tools, to minimize the carbon footprint of plant operations and valorization processes, thereby ensuring alignment with sustainability and carbon-neutrality objectives (Cairone et al., 2025).

Although many WEFE-related technologies are technically mature, their systemic integration within landfills remains an emerging frontier. Current practices often manage waste, LL, LFG and energy demand in isolation rather than through integrated and synergistic approaches. This fragmentation constrains opportunities for sustainable resource recovery and limits the realization of the WEFE Nexus's core objective, consisting of identifying intersectoral inefficiencies while minimizing conflicts across economic, environmental and policy domains. A shift towards co-designed, whole-system planning can unlock greater efficiency, enhance resilience in resource management and generate increased social value.

Key implementation pathways include:

1. Retrofitting existing facilities: many operating landfills already include LFG collection systems, LL treatment units, and capped surfaces suitable for PV systems deployment. Incremental additions, such as PV-powered electrolyzers, methanation reactors, or apiaries, can progressively transform conventional landfills into integrated WEFE hubs.
2. Integrated design: embedding WEFE principles from the conceptual and design stages enables the optimization of spatial layouts, shared utilities and process synergies, thereby reducing both capital costs and the environmental footprint, while increasing the overall performance.
3. Collaborative governance: given the complexity and capital costs of WEFE-integrated landfills, public-private partnerships involving waste operators, energy utilities, technology providers and research institutions are essential to foster innovation and support the implementation.
4. Modular scalability: deploying modular, scalable units allows for progressive implementation, minimizing investment risk while demonstrating technical and economic feasibility.
5. Digital transition and adaptive management: the integration of Internet of things sensors, big data analytics and AI-driven optimization can support real-time monitoring, predictive maintenance and dynamic process control, enhancing operational flexibility and system resilience.

Successful implementation of WEFE-integrated landfill models relies on alignment with supportive policy instruments that take into consideration of the origin of energy for renewable gas production (e.g. green hydrogen mandates) and carbon credits pricing mechanisms (European Commission and Joint Research Centre, 2024). These policies can create favourable conditions for multi-revenue opportunities from bioCH_4 for heavy transport, certified low-carbon hydrogen and renewable electricity exports. Moreover, standardized protocols for biomonitoring will strengthen the required public trust, regulatory compliance and market access (Panseri et al., 2020), ensuring that social, ecological and economic dimensions of the WEFE Nexus are harmonized with next-generation landfill redevelopment.

Conclusion

Valorizing landfills as WEFE Nexus hubs redefines waste infrastructure as productive systems grounded in circular economy principles. Such integrated hubs can showcase the advantages of integrated systems operation as they can simultaneously generate renewable energy, reclaimed water while delivering ecosystem services such as biomonitoring and biodiversity enhancement. This paradigm shift aligns landfill management with global objectives for climate change mitigation, resource conservation, and environmental protection. When properly governed and monitored, WEFE-oriented landfills can evolve into net contributors to sustainable energy systems, water security, local food networks and ecosystem health, acting as active enablers of sustainability. Their integration and systemic operation offer tangible environmental, economic and social co-benefits, underscoring the need for continued research, cross-sectoral collaboration and supportive policy framework to realize their full potential.

Author contributions

Giuseppina Oliva, Stefano Cairone, and Silvia De Paola contributed to writing the original draft. Vincenzo Naddeo conceptualized and supervised the work. Tiziano Zarra, Vincenzo Belgiorno, Antonis A Zorpas, Demetris Lekkas, and Vincenzo Naddeo contributed through review and editing. Generative artificial intelligence (AI) tools were used solely for language editing to improve readability. They did not contribute to research design, data generation, scientific interpretation or content generation, and all AI-suggested edits were reviewed, verified and approved by the authors to ensure accuracy, appropriateness and academic integrity.

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Giuseppina Oliva
Sanitary Environmental Engineering Division (SEED)
Department of Civil Engineering
University of Salerno
Via Giovanni Paolo II #132
84084 Fisciano SA, Italy
Email: goliva@unisa.it

Stefano Cairone
Sanitary Environmental Engineering Division (SEED)
Department of Civil Engineering
University of Salerno
Via Giovanni Paolo II #132
84084 Fisciano SA, Italy
Email: scairone@unisa.it

Silvia De Paola
Sanitary Environmental
Engineering Division
(SEED)
Department of Civil
Engineering
University of Salerno
Via Giovanni Paolo II #132
84084 Fisciano SA,
Italy
Email: sdepaola@unisa.it

Antonis A Zorpas
Laboratory of Chemical
Engineering and Engineering
Sustainability
Faculty of Pure and Applied
Sciences
Open University of Cyprus
Giannou Kranidioti 89, Latsia
Nicosia 2231, Cyprus
Emails: antoniszorpas@yahoo.com; antonis.zorpas@ouc.ac.cy

Tiziano Zarra
Sanitary Environmental
Engineering Division
(SEED)
Department of Civil
Engineering
University of Salerno
Via Giovanni Paolo II #132
84084 Fisciano SA,
Italy
Email: tzarra@unisa.it

Demetris F Lekkas
Waste Management
Laboratory
Department of the
Environment
University of the
Aegean
Mytilene 81100,
Greece
Email: dlekkas@aegean.gr

Vincenzo Belgiorno
Sanitary Environmental
Engineering Division (SEED)
Department of Civil Engineering
University of Salerno
Via Giovanni Paolo II #132
84084 Fisciano SA, Italy
Email: v.belgiorno@unisa.it

Vincenzo Naddeo
Sanitary Environmental
Engineering Division (SEED)
Department of Civil
Engineering
University of Salerno
Via Giovanni Paolo II #132
84084 Fisciano SA,
Italy
Corresponding author.
Email: vnaddeo@unisa.it