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Editorial

Global Challenges and Advances in Energy, Food, and Water Sustainability to Strengthen Climate Resilience

Dorothy Phillips, Robert Wingfield, Laura McConnell, Young-Shin Jun, Amy Prieto, Thalappil Pradeep, Danielle Julie Carrier, Nour Abdoulmoumine, and Jose Ruben Morones-Ramirez*

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■ FROM PARALLEL SUSTAINABILITY CHALLENGES TO COUPLED RESILIENCE

Climate challenges are exposing the limitations of treating energy, food, and water as separate sustainability domains. Energy systems require water, critical materials, resilient infrastructure, and increasingly sophisticated storage technologies. Food systems depend on water availability, energy and chemical inputs, soil functionality, biodiversity, food supply chains, and stable climatic conditions. Water systems, in turn, depend on energy, chemical treatment, monitoring capacity, infrastructure investment, and governance. Stresses in one domain, therefore, rarely remain local: droughts alter energy production and crop yields; floods disrupt sanitation and food supply chains; energy production strategies reshape demand for minerals, water, and land; and waste streams generated in one sector may become valuable feedstocks for another. The central scientific challenge is no longer only to improve individual technologies, but to design systems that perform under coupled environmental, material, and societal constraints.

This joint Special Issue, published across the *Journal of Agricultural and Food Chemistry*, *ACS Agricultural Science & Technology*, *ACS Food Science & Technology*, *ACS ES&T Water*, *ACS ES&T Engineering*, *ACS Sustainable Chemistry & Engineering*, and *ACS Sustainable Resource Management*, was developed in connection with the ACS Presidential and Committee on Science Symposium at ACS Spring 2025, "Global Challenges and Advances in Energy, Food, and Water Sustainability in the Face of Climate Change." The collection brings together Research Articles, Reviews, Viewpoints, and Perspectives that illustrate how chemistry, engineering, environmental science, agricultural science, food science, and resource management can converge around a shared goal: strengthening climate resilience while reducing environmental burdens.

The papers assembled here are diverse in scale and subject matter, but they share an important intellectual direction. They move beyond single-endpoint optimization and toward more integrated thinking about material circularity, process intensification, resource recovery, decentralized infrastructure, agricultural resilience, and system-level assessment. This editorial does not attempt to reduce the collection to one theme. Rather, it highlights how the individual contributions collectively define an emerging research agenda for the energy—food—water—climate nexus.

■ ENERGY INNOVATION, STORAGE, AND CARBON MANAGEMENT

A resilient energy technology requires more than the deployment of additional energy capacity. It requires storage systems that are safer and more sustainable, materials supply chains that are less extractive, catalytic processes that function under realistic conditions, and end-of-life strategies that recover values rather than generate new burdens. The energy-related contributions in this Special Issue address this full arc, from interfacial electrochemistry to recycling, hydrogen technologies, and decentralized bioenergy.

Electrochemical storage is represented by a strong cluster of studies on aqueous zinc-ion, lithium—sulfur, and thermal management systems. For aqueous zinc-ion batteries, polymer electrolyte additives regulate zinc deposition through a tube-sieve mechanism (10.1021/acssuschemeng.5c08772), γ-aminobutyric acid is introduced as a biodegradable additive to stabilize zinc metal anodes (10.1021/acssuschemeng.5c10007), and activated-carbon coatings on MnO_2 cathodes suppress inactive manganese species and improve cathode performance (10.1021/acssuschemeng.5c11037). In lithium—sulfur chemistry, a rectifying MoO_2/nitrogen-deficient carbon nitride heterojunction accelerates electron and ion transport while promoting polysulfide conversion (10.1021/acssuschemeng.5c09447). At the device safety interface, cross-linked polyurethane phase-change composites show how thermal management materials can help address high-load battery operation (10.1021/acssuschemeng.5c06079). These studies illustrate how nanoscale and molecular-scale control of interfaces can translate into practical improvements in stability, kinetics, and safety.

Material circularity is treated in this collection as a design requirement for carbon management rather than as a downstream waste management problem. One-pot persulfate leaching combined with sol—gel regeneration provides a closed-loop route for spent lithium-ion cathodes (10.1021/acssuschemeng.5c09673), while molten-salt-assisted direct upcycling converts spent polycrystalline NCM523 cathodes into single-crystalline materials with improved electrochemical performance (10.1021/acssuschemeng.5c06917). A perspective on battery-grade graphite recycling identifies a critical but often underdiscussed element of the battery supply chain (10.1021/acssusresmgt.5c00312) and a life-cycle assessment of lithium carbonate production from eleven global brine operations situates battery materials within broader environmental accounting (10.1021/acssuschemeng.5c03739). Together, these contributions make clear that climate mitigation technologies must be evaluated not only by their operational performance, but also by the resource systems that sustain them.

Hydrogen, electrolysis, and resource recovery further expand the energy frame. A self-supported NiCrP−NiP heterostructure on polyurethane sponge enables corrosion-resistant bifunctional catalysis for seawater electrolysis (10.1021/acssuschemeng.5c07766), and triazine-branched poly(aryl piperidinium) anion-exchange membranes advance conductivity and alkaline durability for anion exchange membrane (AEM) water electrolyzers (10.1021/acssuschemeng.5c06324). Hydrogen is also used in a membrane-free chemical desalination strategy at room temperature, directly linking energy carriers with water security (10.1021/acssusresmgt.5c00509). Oxygen-evolution catalysis is advanced through copper-doped double-shell $CuCo_2S_4$ nanospheres that shift activity toward a lattice-oxygen mechanism (10.1021/acssuschemeng.5c04644). Other contributions demonstrate selective recovery of gold and copper from electronic waste using a CNC pincer-type ionic liquid (10.1021/acssusresmgt.5c00497), production of hydrogen-rich syngas from sewage-sludge pyrolysis over Ni−Fe/Al_2O_3 catalysts (10.1021/acssuschemeng.5c07927), and a dual-chamber microbial fuel cell fabricated from recycled aluminum cans and natural materials (10.1021/acssusresmgt.5c00473). Across these papers, energy sustainability is inseparable from water use, waste valorization, critical mineral and material recovery, and locally adaptable infrastructure.

■ WATER SECURITY, TREATMENT, AND REUSE

Water is the medium through which many climate impacts become immediately visible. Droughts constrain agriculture and energy production. Floods compromise sanitation and mobilize contaminants. Wastewater systems face increasing pressure to remove pollutants, recover resources, lower emissions, and operate reliably despite variability. Common in infrastructure-limited regions, the mixing of stormwater and wastewater can contribute to system-capacity overload, undermines water-system reliability, and is further intensified by climate vulnerability. The water-focused contributions in this collection therefore span sensing, treatment chemistry, process engineering, carbon management, and socio-technical resilience.

Several papers strengthen the analytical and treatment foundations of water quality management. A systematic evaluation of $LiNO_3$, $NaNO_3$, and KNO_3 electrolytes in commercial photoelectrochemical oxygen-demand devices clarifies how conductivity and electrolyte identity influence sensing performance (10.1021/acsestwater.5c00125). Alum coagulation is benchmarked across 26 wastewater effluents, providing quantitative insight into effluent organic matter removal and the limitations of models developed for surface-water contexts (10.1021/acsestengg.5c00614). A schwertmannite/iron phosphide composite extends heterogeneous Fenton activity over a broad pH range by enhancing Fe(II)/Fe(III) cycling (10.1021/acsestwater.5c00474). Process-level advances include bioflocculation−CaO pretreatment integrated with sequencing batch reactor operation for swine wastewater containing copper and zinc (10.1021/acsestwater.5c00912), as well as electrodialysis for ammonia recovery from real and synthetic wastewater mixtures, where hardness is shown to influence specific energy consumption (10.1021/acsestwater.5c00721). These studies demonstrate the continuing need to connect mechanism, matrix complexity, and operational performance.

A second water theme centers on reframing wastewater and aquatic systems as platforms for resource recovery and climate mitigation. Pilot-scale encapsulated anaerobic biological treatment enables decentralized methane recovery from food and beverage wastewater (10.1021/acsestengg.5c00917). Hydrothermal carbonization of sugarcane bagasse mediated by fresh sewage and compost leachate reduces freshwater demand while producing energy-dense hydrochar (10.1021/acsestengg.5c00542). A coupling-coordination-degree framework integrates gray water footprint reduction with carbon emission intensity to evaluate dynamic pollution−carbon co-management in full-scale wastewater treatment plants (10.1021/acsestengg.5c00834). The role of biochar as a carbon dioxide removal strategy is examined through a bibliometric synthesis of carbon persistence studies (10.1021/acsestwater.5c00606), while measurements of CO_2 fluxes in urban rivers and lakes show that vegetation density can modulate aquatic carbon exchange (10.1021/acsestwater.5c00558). A long-term analysis of atmospheric humidity in arid Xinjiang extends the discussion to regional hydrometeorological change and its implications for water sustainability (10.1021/acsestwater.5c01076).

The collection also reminds us that resilient water systems are not only chemical or engineered systems; they are socio-technical systems. Household surveys across Nepal, Ethiopia, and Uganda identify infrastructural and demographic factors that influence sanitation failure under flooding (10.1021/acsestwater.5c01055). A Viewpoint on science diplomacy argues that environmental resilience in a fractured world requires renewed cooperation across national and institutional boundaries (10.1021/acsestwater.5c01146). A review of polymer-supported nanomaterials for water treatment complements these perspectives by synthesizing material platforms with potential relevance to next-generation remediation (10.1021/acsestwater.5c00476). The result is a broad view of water security in which molecular innovation, process design, infrastructure vulnerability, and governance all matter.

■ SUSTAINABLE FOOD SYSTEMS AND AGRICULTURE

Climate-resilient food systems must maintain productivity, nutritional quality, and safety under increasing water stress, soil degradation, pest pressure, and supply chain uncertainty. The food and agricultural contributions in this Special Issue show how chemical, biological, and engineering approaches can improve resilience from soil and plant physiology to food processing and waste management.

Soil health and plant stress tolerance are central to this agenda. A review of microbiome-mediated salt-stress mitigation synthesizes how microbial communities influence phytohormone balance, nutrient acquisition, biofilm formation, and plant adaptation under salinity (10.1021/acsagscitech.5c00443). A sulfide-infused FeS−palygorskite nanohybrid improves iron availability in alkaline soils and enhances soybean germination, biomass, and chlorophyll content (10.1021/acs.jafc.5c12843). Precision-agriculture decision-making is advanced through the comparison of visible−near-infrared, mid-infrared, and fused spectroscopic strategies for predicting soil properties at multiple depths (10.1021/acsagscitech.5c00345). In drought-stressed grafted grapevines, amino-acid profiling reveals how rootstock selection contributes to physiological resilience in arid cultivation systems (10.1021/acsagscitech.5c00540). Selenium-enriched biochar reduces mercury bioavailability in garlic under elevated CO_2 while increasing selenium nutrition (10.1021/acs.jafc.5c08463), and histological analysis of Brassicaceae microgreens grown under twelve LED spectra identifies lighting strategies relevant to controlled-environment agriculture (10.1021/acsagscitech.5c00510). Collectively, these studies show that resilience is built through the linked control of soil chemistry, plant physiology, microbial function, and cultivation environment.

Biotic interactions, pest management, and food safety are addressed through complementary molecular and applied approaches. Gas chromatography–mass spectrometry (GC−MS) metabolomic analysis of coffee seedlings shows that neonicotinoid exposure perturbs sugar metabolism and alkaloid biosynthesis even at sublethal doses (10.1021/acsagscitech.5c00439). Transcriptomic analyses of *Spodoptera frugiperda* salivary glands identify salivary protein genes associated with host adaptation across plant species (10.1021/acs.jafc.5c07280). In food safety microbiology, regulatory studies of *Bacillus cereus* biofilm formation define the FtsH−Spo0A axis as a potential control point (10.1021/acs.jafc.5c10623). Plant-disease control is advanced through arecoline derivatives incorporating a quinazolin moiety with antifungal activity against *Colletotrichum camelliae* in tea plants (10.1021/acs.jafc.5c07837). Food engineering is represented by response-surface optimization of hamburger buns formulated with organogels, linking product quality to more sustainable lipid structuring (10.1021/acsfoodscitech.5c00445). A Viewpoint on agricultural effluents reframes these streams as potential resources rather than unavoidable pollutants (10.1021/acsagscitech.5c00471). These contributions emphasize that the sustainability of food system will depend on interventions that operate across biological regulation, process design, and circular resource use.

■ CIRCULAR ECONOMY AND CROSS-CUTTING CLIMATE SOLUTIONS

Perhaps the most integrative papers in the collection are those that convert residual streams into functional materials, adsorbents, fuels, or bioprocess inputs. These studies are important because they operationalize nexus thinking: waste in one domain becomes a resource in another, and environmental remediation is coupled to value creation.

Rice husk is fractionated into lignin nanoparticles, silica nanoparticles, cellulose nanocrystals, and cellulose nanofibers for Pickering emulsion applications, establishing a single-feedstock platform for renewable interfacial materials (10.1021/acssusresmgt.5c00421). The marine macroalga *Caulerpa lentillifera* is evaluated through a waste-free utilization framework that integrates extraction, protein recovery, antioxidant profiling, and dye adsorption (10.1021/acssusresmgt.5c00260). Corn distiller solubles are transformed into zinc−phosphorus-doped carbon microspheres for methylene-blue adsorption (10.1021/acssusresmgt.5c00524). Bivalve shells are thermally transformed into polymorphic adsorbents for dye remediation (10.1021/acssusresmgt.5c00366), and waste cooking oil is converted into water-soluble carbon nano-onions that enhance *Chlorella pyrenoidosa* cultivation for simultaneous COD abatement and biofuel-precursor production (10.1021/acssusresmgt.5c00276).

These contributions point to a broader design principle: circularity is most powerful when it is specific, measurable, and chemically grounded. It is not enough to claim that a residue has value. The field must show how composition, structure, reactivity, logistics, safety, and life-cycle performance determine whether that value can be realized. Across the Special Issue, this same principle appears in battery upcycling, wastewater resource recovery, biochar carbon persistence, agricultural effluent valorization, and biomass-derived materials. In that sense, circular economy is not a separate topic within the collection; it is one of the organizing logics of climate-resilient chemistry and engineering.

■ FORWARD OUTLOOK: PRIORITIES FOR THE NEXT PHASE OF NEXUS RESEARCH

Reading across the contributions, five priorities emerge. First, translation under realistic operating conditions must become central. Many advances in batteries, catalysts, membranes, adsorbents, bioprocesses, agricultural amendments, and food formulations are promising at laboratory scale, but climate resilience will depend on performance under variable feedstocks, complex matrices, fluctuating energy inputs, diverse soils, and imperfect infrastructure. Second, systems accounting must mature. Nexus research should increasingly quantify trade-offs among carbon emissions, water demand, land use, material criticality, cost, toxicity, durability, and social benefit rather than relying on single sustainability metrics.

Third, circularity must be evaluated with accountability. Waste valorization is most convincing when supported by robust mass balances, realistic process logistics, product safety, technoeconomic considerations, and life-cycle assessment. Fourth, equity and geographic specificity must be treated as design criteria rather than as afterthoughts. Several papers in this collection address settings where drought, flooding, sanitation fragility, limited infrastructure, and resource constraints intersect; expanding such perspectives is essential if climate-resilience research is to be globally relevant. Fifth, shared data and comparable metrics are needed to accelerate learning across journals and disciplines. Standardized reporting, open datasets, harmonized testing conditions, and transparent life-cycle inventories would make it easier to compare technologies and identify deployment pathways.

The value of this Special Issue lies not in proposing a single answer to the climate challenge, but in demonstrating the capacity of the scientific community to work across boundaries. Chemistry and engineering are present here not only as tools for making better materials, catalysts, membranes, sensors, foods, and treatment systems, but also as disciplines capable of connecting molecular design to environmental performance and societal resilience. The next phase of work at the energy−food−water−climate nexus should build on this foundation by

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moving from promising components to integrated systems that can be scaled, governed, and adapted to local needs.

In this sense, the collection is both a record of current progress and an invitation. It invites researchers to design technologies with their full resource context in mind; to connect laboratory performance with field conditions; to recognize waste streams as potential material and energy flows; to integrate carbon, water, food, and energy accounting; and to treat resilience as a measurable, shared objective. The challenges are global, but the solutions will be built through many locally grounded advances of the kind represented in this Special Issue. We realize that challenges in energy, food, and water will be overcome sustainably only by integrating traditional knowledge with advanced science, ensuring biodiversity in the One World framework.

AUTHOR INFORMATION

Corresponding Author

Jose Ruben Morones-Ramirez – *Facultad de Ciencias Químicas, Universidad Autónoma de Nuevo León (UANL), San Nicolás de los Garza 66455, México; Centro de Investigación en Biotecnología y Nanotecnología, Facultad de Ciencias Químicas, Universidad Autónoma de Nuevo León, Parque de Investigación e Innovación Tecnológica, Apodaca 66628, México;* orcid.org/0000-0001-7009-686X; Email: jose.moronesrmr@uanl.edu.mx

Authors

Dorothy Phillips – *Immediate Past President 2026, President 2025, American Chemical Society, Washington, District of Columbia 20036-4892, United States*

Robert Wingfield – *Fisk University, Nashville, Tennessee 37208-4501, United States*

Laura McConnell – *Bayer Crop Science, St. Louis, Missouri 63167, United States;* orcid.org/0000-0001-6142-0656

Young-Shin Jun – *Washington University in St. Louis, St. Louis, Missouri 63130-4899, United States;* orcid.org/0000-0003-4648-2984

Amy Prieto – *Colorado State University, Fort Collins, Colorado 80523, United States; Prieto Battery, Inc., Fort Collins, Colorado 80524, United States;* orcid.org/0000-0001-9235-185X

Thalappil Pradeep – *Indian Institute of Technology Madras, Chennai 600036, India;* orcid.org/0000-0003-3174-534X

Danielle Julie Carrier – *University of Tennessee, Knoxville, Tennessee 37996, United States;* orcid.org/0000-0003-3322-4660

Nour Abdoulmoumine – *University of Tennessee, Knoxville, Tennessee 37996, United States;* orcid.org/0000-0001-6586-5919

Complete contact information is available at:
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