Advancing Circular Bioeconomy in the GCC Region through Hydrothermal Treatment: Insights from BioFairNet's Pilot Site 1

Prof. Dr. Stergios Vakalis, Thermodynamics and Transport Phenomena Laboratory, School of Chemical Engineering, National Technical University of Athens, 9 Heroon Polytechniou, GR-15780, Athens, Greece

Authors CV

Dr. Stergios Vakalis is an Assistant Professor of Energy Processes at the School of Chemical Engineering, National Technical University of Athens. Stergios works primarily on energy analysis, thermochemical production of biofuels and modeling of energy processes. He is also a member of the Editorial Board for the academic journal Nature Scientific reports (Springer), and a member of the Committee of the Global Waste-to-Energy Research and Technology Council – WtERT®. Previously, he was an Associate Professor of "Low Carbon Energy Technologies" at the Department of Environment, University of the Aegean and the Director of the Energy Management Laboratory. He studied Environmental Engineering at the Technical University of Crete and got an MSc in Sustainable Resource Management from the Technical University of Munich. He received his PhD in Sustainable Energy and Technologies at the Free University of Bolzano for his doctoral dissertation on biomass gasification.

Abstract

The Gulf Cooperation Council (GCC) has developed impressive national road-maps that pledge deep decarbonization, landfill diversion and water security by 2030–2050. Hydrothermal treatment (HT)—an umbrella term covering primarily hydrothermal carbonization (HTC, 180–250 °C) and hydrothermal liquefaction (HtL, 280–370 °C)—is uniquely suited to the region's wet organic residues, which include food waste, sewage sludge, algal blooms and agro-processing effluents. HT sidesteps the energy-intensive drying that hampers pyrolysis and incineration, yielding three co-products: carbon-rich hydrochar, energy-dense bio-oil and a nutrient-laden process liquor. Yet only two pilot-scale plants operate across six GCC states, and no published analysis quantifies the combined benefits of landfill diversion, desalination heat-integration and green-hydrogen synergies that HT can deliver. This study presents laboratory campaigns on dairy effluent, sewage sludge and other biowaste that have the scope to maximize either hydrochar HHV (up to 28 MJ kg^{-1} at 250 °C, 60 min) or bio-crude yield (33 % at 320 °C). A process-integration system, i.e. the HYDROPYR, is developed int framework of the BioFairNet project and couples and HT reactor with a PV system and a pyrolyzer. Finally, we present the hierarchical SMAA-PROMETHEE

decision framework to rank feedstock–severity combinations under competing stakeholder priorities—energy yield, nutrient recovery, cost and carbon abatement.
Results show that solar-assisted HTC of mixed food waste delivers a cradle-to-gate global-warming potential of –0.74 kg CO_2-eq kg^{-1} hydrochar. Comparative benchmarking against the EU-funded BioFairNet Pilot Site 1 (Lesvos, Greece) highlights two transferable lessons: (i) modular, skid-mounted reactors simplify siting on wastewater-treatment plants, and (ii) open-hardware sensor suites enable the granular ESG reporting that Gulf regulators increasingly demand. The paper concludes that HT, when supported by RES and potentially also coupled with solar-powered desalination and hydrogen production, can shift the GCC to a genuinely circular bioeconomy. Policy levers such as waste-to-energy tariffs pegged to avoided landfill cost, carbon-offset certification for negative-emission hydrochar, and "water-footprint" credits for brine-polishing liquor are pivotal to unlock the first wave of commercial projects by 2030.

1. Introduction

The Gulf Cooperation Council (GCC) finds itself balancing two opposing trends: exceptionally high use of materials and water on a per-capita basis, and a bold suite of national roadmaps—led by Saudi Arabia's Vision 2030 and echoed in the UAE, Oman, Qatar, Bahrain and Kuwait—that aim to cut carbon, eliminate waste and bolster water security in one of the world's driest regions. Hydrothermal treatment (HT)—a set of 180 – 350 °C processes that transform wet organics into hydrochar, biocrude and nutrient-rich liquor—could serve as a regional "hat-trick": it keeps moisture-laden waste out of landfills, yields carbon-negative fuels for difficult-to-decarbonize industries, and supplies process water that can merge with saline streams. Apart from a handful of Saudi and Emirati pilots, however, the Gulf still lacks comprehensive data on HT. This paper therefore frames HT against the GCC's sustainability agenda and outlines a vision for solar-powered HT hubs knit into advanced desalination plants and the nascent green-hydrogen export network.
Gulf master plans—Saudi Vision 2030, UAE Net-Zero 2050 and Oman Vision 2040—declare that "waste is a resource" and water security is non-negotiable. Targets include diverting more than four-fifths of Saudi waste from landfill by 2035, building a multi-billion-dollar recycling market and raising renewables to half of the power mix by 2030, while the UAE pledges to cut food waste in half and top the Global Food Security Index by mid-century. Yet urban centers such as Riyadh, Doha, Abu Dhabi and Dubai still produce over 1.5 kg of municipal waste per person each day, with organics exceeding 40 %. Household water use exceeds 500 L capita^{-1} day^{-1}—quadruple German levels—forcing the operation of more than 1,600 desalination units. Conventional gas-fired desalination, however, emits roughly 1.5 kg CO_2 and discharges an equivalent volume of hypersaline brine for every cubic metre of fresh water, threatening to offset wider decarbonisation gains. These intertwined waste and water pressures heighten the case for integrated, low-carbon solutions such as HT.

Hydrothermal carbonization (HTC) studies now converge on a clear mechanistic picture: reaction “severity” (temperature × time) dictates both de-oxygenation and nutrient partitioning, with higher severities accelerating carbon condensation at the expense of nitrogen and phosphorus retention in the solid phase. Experiments with dairy-plant effluents and mixed sewage slurries illustrate the trade-off: COD removal rises while NH_4^+ and PO_4^{3-} migrate into the process liquor, and hydrochar yield falls from roughly half to one-third of the dry feed as the process shifts toward hydrothermal liquefaction . Across diverse substrates—agro-digestates, municipal-sludge cakes, olive-mill sludge, anise residues and spent coffee grounds—moderate HTC (≈200 °C, 2–4 h) reliably upgrades the solid fraction to heating values of 23–28 MJ kg^{-1}, comparable to low-rank coal, while enhancing porosity and occasionally acting as an electron shuttle when re-introduced into anaerobic digesters . Integrated process chains that recycle nutrient-rich liquors, couple HTC heat with downstream AD or membrane desalination, and exploit multi-criteria decision tools (e.g., Hierarchical-SMAA-PROMETHEE) demonstrate that carbon-negative fuel, wastewater polishing and circular fertiliser production can be co-optimised rather than traded off .

Hydrothermal liquefaction (HtL) is a high-temperature, high-pressure upgrading route that converts wet organic streams directly into an energy-dense bio-crude, a process water rich in soluble organics and nutrients, and a small fraction of solid residue. Whereas hydrothermal carbonisation typically operates below 250 °C, HtL pushes the reaction zone to roughly 280–370 °C and 10–25 MPa, creating sub-critical water that behaves as a non-polar solvent; this shifts the dominant pathways from dehydration and polymerisation toward decarboxylation, depolymerisation and hydrogen-transfer reactions that favour liquid formation. Experiments that gradually raised temperature on municipal-sludge slurries from 200 °C to 325 °C showed hydrochar yields collapsing from ~46 % to ~31 % (dry basis) while bio-crude output and off-gas CO_2 climbed sharply—a clear kinetic transition from HTC to full HtL behaviour . Similar trends appear in spent-coffee-ground trials, where bio-crude quality evolves from phenolic-rich at 300 °C to fatty-acid-methyl-ester-rich above 360 °C, and the hydrochar fraction dwindles to roughly one quarter of the feed with a higher-heating value (HHV) near 33 MJ kg^{-1} .

2. The BioFairNet Project

BioFairNet is a 2025-28 Horizon Europe Innovation Action that sets up a “Green Information Factory”—a digital clearing-house where agrifood and mining actors co-design low-carbon value chains. The concept is stress-tested in two real-world pilots, the first of which is on Lesvos (North Aegean, Greece). Lesvos qualifies as a Just-Transition hotspot because 54 olive mills and 18 dairy plants discharge more than 250 000 t yr^{-1} of nutrient-rich wastewater and about 30 000 t yr^{-1} of olive-tree prunings, together releasing roughly half a tonne of CO_2-equivalent per tonne of waste when unmanaged. Pilot Site 1 turns this liability into an asset through PV-assisted hydropyrolysis (HYDROPYR): olive-mill effluent, pomace and prunings first undergo hydrothermal carbonisation at 200–280 °C, 20–60 bar, then the wet hydrochar is immediately pyrolysed at 500–900 °C to yield high-fixed-carbon “biocarbon.” A refurbished 8 L, 1000 psi HTC reactor—augmented with a tubular furnace, catalyst doser and 3 kW rooftop PV array—operates semi-continuously at 50–100 kg mixed feed day-¹.

The activities on the pilot site are separated in tasks: (i) detailed feedstock and product characterisation, (ii) pilot construction and safety validation, (iii) laboratory optimisation with Parr reactors, (iv) two years of seasonal campaigns under a fast-and-continuous smart-supervisory (F\&CSS) system, and (v) techno-economic and life-cycle modelling with HOMER Pro and SuperPro Designer. Open-hardware sensor stations stream gas, energy and mass-flow data to the Green Information Factory, enabling real-time fault detection and providing harmonised LCA, LCC and social-LCA inputs. The pilot targets a near-zero—or negative—carbon footprint by displacing open burning and landfilling, while the resulting biocarbon can serve as a soil amendment or conductive additive in anaerobic digestion, and the treated liquor may be recycled as process water. Accompanying reskilling schemes align with Greece’s Just-Transition agenda, and scale-up studies explore boosting throughput beyond 100 kg day-¹ with battery-backed PV to increase the renewable share.

Figure 1. The Pilot Site of BioFairNet in Lesvos island

3. Methodology

Samples of dairy effluent, municipal- and agro-digestate, sewage sludge, OMWW and wine sludges were taken in line with EN 14778. Several pressure reactor systems were utilized: (i) a 25 mL PTFE-lined micro-reactor for 120–200 °C dairy runs. (ii) a 4 L stainless autoclave (200 °C, 150 bar) for 20 wt % digestate slurries; (iii) a 1 L Parr 4577A reactor was utilized for the main core of the hydrothermal experiments. It is a continuously stirred Parr CSTR reactor that ramped wastewater from 200 °C (for HTC) up to the 350 °C (which is the liquefaction window). Reaction severity ranged in accordance to the residence time and the temperature of operation while full mass- and energy-balances were assessed.

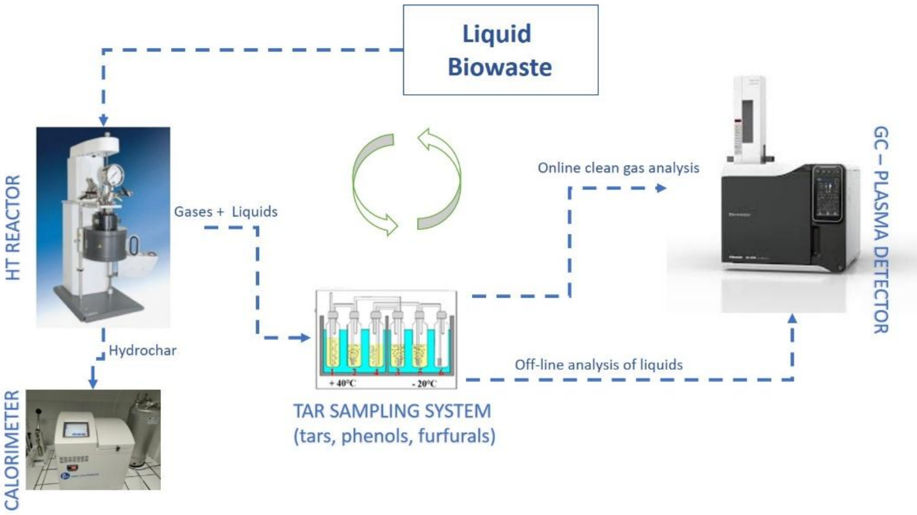

Figure 2. The main instrumentation: An HT reactor, A GC-BID, a tar sampling system, and a Calorimetric analyzer.

Post-treatment solids were filtered, oven-dried and characterized by proximate/ultimate analysis, BET surface-area (N_2 adsorption) and higher-heating-value determination on a bomb calorimeter. HT liquors were passed through 0.45 µm filters and examined for COD following APHA Standard Methods, and along with nitrates and phosphates were measured on a Hach spectrophotometer. Bio-crude fractions were solvent-extracted and profiled on a Shimadzu Nexis 2030 GC-BID (for phenolics, VFAs and FAMEs. Produced permanent gases were also measured by means of the GC-BID system with the utilization of a ShinCarbon 80/100 micropacked column. Two-way ANOVA tested the influence of temperature and residence time.

4. Results

Hydrothermal carbonization (HTC) markedly enriched the solid fraction of all tested wet residues. Crop- and MSW-digestates treated at 250 °C for 60 min showed a ~28 % rise in fixed-carbon, a doubling of meso-/macropore volume and an increase in higher-heating value (HHV) from roughly 17 to 24 MJ kg^{-1}. For dairy-plant effluent, chemical-oxygen demand fell by about 17 % as temperature climbed from 120 °C to 200 °C, but nitrates and phosphates in the process liquor spiked to 427 mg L^{-1} and 410 mg L^{-1}, respectively, confirming that harsher conditions clean the carbon matrix while mobilizing nutrients. Olive- and wine-sludge hydrochars reached HHVs of 26–28 MJ kg^{-1}; adding 4 g L^{-1} of the wine-sludge char to batch anaerobic digesters lifted biogas production to 211 mL g VS^{-1}—about 30 % above the control—highlighting the material's potential as a redox mediator as well as a fuel.

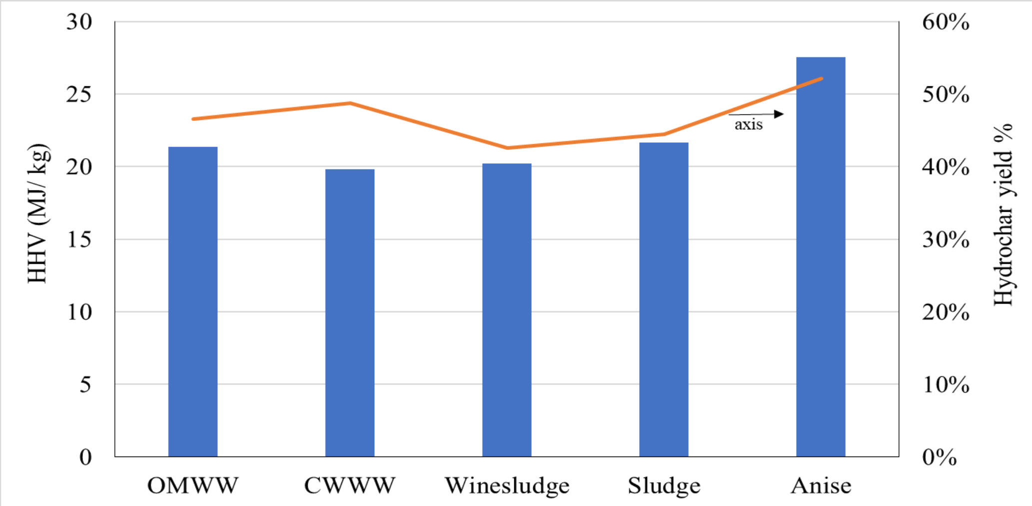

Figure 3. HHV and mass yields of hydrochar- published results: Vasileiadou et al. (2022); Altiparmaki et al., (2022); Chatzimaliakas et al., (2021); Vakalis et al., (2021)

Shifting into the hydrothermal-liquefaction (HtL) regime inverted the product slate. When sewage-sludge slurries were ramped from 200 °C to 325 °C, solid yield collapsed from 46 % to 31 % (dry basis) while the bio-crude fraction climbed to 26 % and off-gas CO_2 approached 90 % of the gas stream, signaling the transition from polymerization-dominated HTC to depolymerization and decarboxylation typical of full HtL. Spent-coffee-ground runs at 350 °C captured 34 % of the initial carbon in the oil phase; the residual hydrochar—only 26 % of the feed—logged an HHV of 32.9 MJ kg^{-1}, and oil composition shifted from phenolic-rich at 300 °C to fatty-acid-methyl-ester-rich above 360 °C, desirable for refinery blending. Implementing a two-stage "HTC → HtL" sequence reduced specific heat demand by roughly one-quarter relative to a single-step HtL benchmark, thanks to easier solids handling and the reductive role of the intermediate hydrochar.

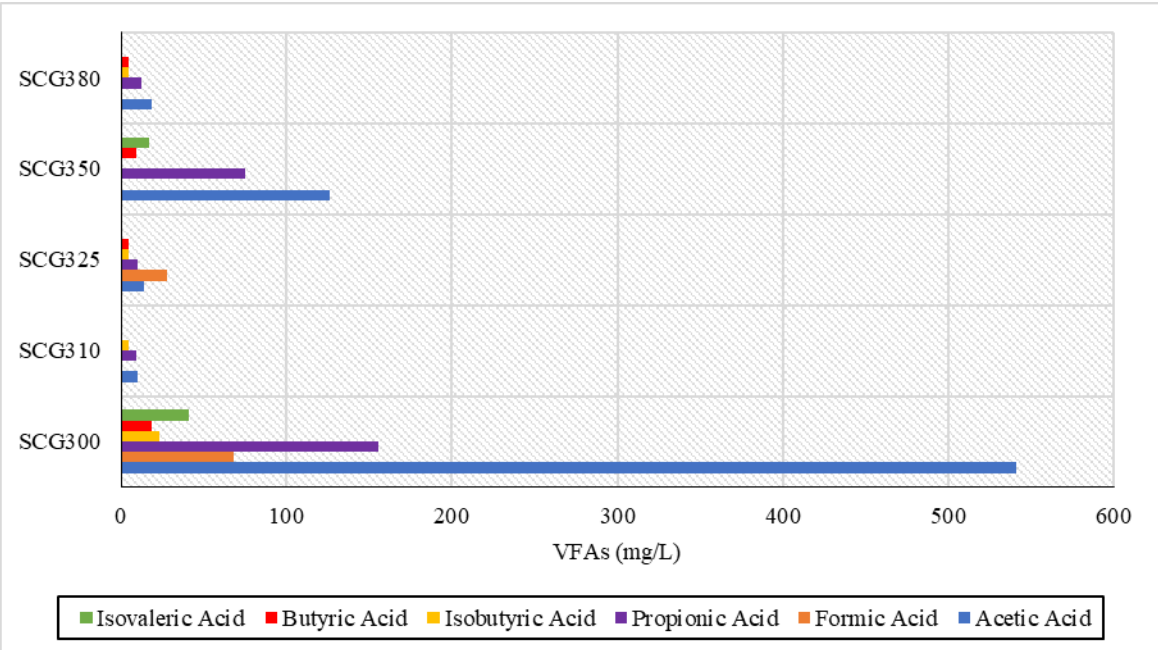

Figure 4. VFAs in HtL biocrude (Liakos et al. 2025)

Lifecycle calculations based on food-industry residues indicate net greenhouse-gas savings of 0.6–0.9 t CO_2-eq per tonne of dry feed when the aqueous phase displaces mineral fertiliser and the bio-crude substitutes low-sulphur fuel oil; energy-return-on-investment values exceed four under those assumptions. Collectively, the findings show that careful tuning of temperature–time "severity," combined with downstream nutrient recovery and energy-efficient sequencing, can transform high-moisture wastes into market-competitive fuels and carbon materials while delivering substantial climate benefits.

5. Discussion and Vision for the Gulf Region

TEA analysis suggests that hydrothermal plants can reach break-even in the Gulf once two parameters are taken into consideration: cheap power and rising landfill charges. Wholesale electricity for industry in Saudi Arabia is lower than 7 ¢/ kWh which one of the lowest in the G20—so reactor heating contributes less than 15 % of total operating expense. On the other hand, several emirates and Saudi municipalities are studying the increase of landfill tariffs. When those charges are credited as "avoided cost," hydrothermal carbonization (HTC) will become a very beneficial endeavor.
Policy levers and strategic fit: Two policy instruments could accelerate deployment. First, a waste-to-energy tariff connected to the avoided landfill cost would guarantee a floor price for hydrochar or biocrude without straining public budgets. Second, Saudi Arabia's emerging offset market and the UAE's voluntary carbon exchanges could recognize the negative-emission potential of hydrochar (–0.74 kg CO_2-eq kg^{-1}) and marine-algae biocrude (≈ 33 % yield at 320 °C), unlocking an additional US 15–40/ t of revenue stream.
Lessons from BioFairNet Pilot 1: The Lesvos HYDROPYR demonstrator operates at 50–100 kg/ d and streams real-time mass- and energy-balance data to a "Green Information Factory". Translating that template to the Gulf means prioritizing modular reactors that can be craned onto wastewater-treatment plants, pairing them with rooftop photovoltaics or CSP and adopting the same open-hardware sensor stack to support Gulf regulators' growing demand for traceable ESG metrics. A potential roadmap for municipal-scale HTC units deployed on WWTPs by 2030, followed by regional HtL refineries feeding sustainable aviation fuel and bio-naphtha after 2035 will increase the production of carbon-negative resources tailored to the GCC's circular-economy vision.
A Decision Making Tool: A multi-criteria decision tool such as the hierarchical SMAA-PROMETHEE framework can turn a trial-and-error search for "good" hydrochar or biocrude into a structured optimization exercise. By scoring candidate chars and oils simultaneously on energy density, ash content, nutrient value, production cost and any site-specific constraints, the tool reveals which feedstock–temperature–time – pH combinations deliver high performance across the whole indicator set rather than excelling in just one dimension. Because SMAA explores thousands of weight scenarios, it highlights solutions that remain top-ranked even when decision priorities

shift, allowing plant operators to adjust severity, solids loading or post-treatment steps with confidence that overall hydrochar/ biocrude quality will improve rather than simply trade one benefit for another.

6. Conclusion

This research demonstrates that hydrothermal treatment can convert the GCC's most troublesome wet waste into carbon-negative fuels, nutrient carriers and heat streams and can work together with existing desalination and forthcoming hydrogen hubs. Laboratory data confirm that moderate HTC conditions (≈ 200–250 °C) maximize hydrochar quality, while higher-temperature HtL favors bio-crude yields suitable for refinery co-processing. Life-cycle metrics reinforce the climate case: each ton of wet feed diverted from landfill can avoid up to 0.9 t CO_2-eq. Translating these results into bankable projects requires a focused policy package: a) A gate-fee-indexed waste-to-energy tariff would stabilize revenue without burdening public budgets. B) Voluntary carbon markets in Riyadh and Abu Dhabi can monetize hydrochar's negative-emission profile.
Lessons from the BioFairNet demonstrator—modular reactor design, photovoltaic heat-assist and real-time data logging—offer an implementation blueprint. Hydrothermal hubs co-located with wastewater-treatment plants can form the backbone of a Gulf circular-bioeconomy strategy: municipal-scale HTC units by 2030, followed by regional HtL refineries supplying sustainable aviation fuel and bio-naphtha thereafter. With supportive tariffs and robust monitoring, the GCC can leapfrog incremental recycling models and position HT as a pillar of its Vision 2030 resource-security agenda.

7. References

- Altiparmaki, Georgia, María A. Vasileiadou, and Stergios Vakalis. 2022. "The Effect of Excess Water on the Hydrothermal Carbonization of Anise Waste from Ouzo Production on Lesvos Island." Sustainable Chemistry and Pharmacy 29: 100831. https://doi.org/10.1016/j.scp.2022.100831.
- Altiparmaki, Georgia, Petros Kourletakis, Konstantinos Moustakas, and Stergios Vakalis. 2022. "Assessing the Effect of Hydrothermal Treatment Severity on the Fate of Nitrates and Phosphates in Dairy Wastewater." Fuel 312: 122866. https://doi.org/10.1016/j.fuel.2021.122866.
- Chatzimaliakas, P. F., A. Iliopoulou, and S. Vakalis. 2020. "The Effect of Acidic Pretreatment on the Hydrothermal Carbonization of Cheese-Whey Wastewater (CWW): The Case Study of Lesvos Island." Paper presented at the 29th European Biomass Conference and Exhibition (EUBCE), Marseille (hybrid event), 26–29 April.
- Isigonis, Panagiotis, Salvatore Corrente, and Stergios Vakalis. 2024. "A Framework for Assessing Hydrochars from Hydrothermal Carbonisation of Agrowaste with the Use of MCDA: Application with the Hierarchical SMAA-PROMETHEE Method." Sustainability 16: 410. https://doi.org/10.3390/su16010410.

- Liakos, Dimitrios, Georgia Altiparmaki, Alexandros Kalampokidis, Dimitrios F. Lekkas, and Stergios Vakalis. 2023. “Co-Digestion of Cheese Whey Wastewater with Hydrochars Originating from Wine Sludge and Olive-Mill Wastewater.” Sustainable Chemistry and Pharmacy 35: 101153. https://doi.org/10.1016/j.scp.2023.101153.
- Liakos, Dimitrios, Georgia Altiparmaki, Konstantinos Moustakas, Simos Malamis, and Stergios Vakalis. 2024. “The Fate of Volatile Fatty Acids during the Thermodynamic Transition from Hydrothermal Carbonization to Hydrothermal Liquefaction: HtC-to-HtL.” Sustainable Chemistry and Pharmacy 41: 101683. https://doi.org/10.1016/j.scp.2024.101683.
- Liakos, Dimitrios, Georgia Altiparmaki, Simos Malamis, and Stergios Vakalis. 2025. "Hydrothermal Liquefaction for Biofuel Synthesis: Assessment of VFA (Volatile Fatty Acid) and FAME (Fatty Acid Methyl Ester) Profiles from Spent Coffee Grounds" Energies 18, no. 8: 2094. https://doi.org/10.3390/en18082094
- Pawlak-Kruczek, Halina, Łukasz Niedźwiecki, Małgorzata Sieradzka, Agata Młonka-Mędrala, Marcin Baranowski, Monika Serafin-Tkaczuk, and Aneta Magdziarz. 2020. “Hydrothermal Carbonization of Agricultural and Municipal Solid Waste Digestates—Structure and Energetic Properties of the Solid Products.” Fuel 275: 117837. https://doi.org/10.1016/j.fuel.2020.117837.
- Borazjani, Ziba, Reza Azin, Shahriar Osfouri, Rahim Karami, Eric Kennedy, and Michael Stockenhuber. 2025. “Hydrothermal Liquefaction of Caulerpa sertularioides: Optimized Biocrude Production and Characterization with Pretreatment Techniques.” Biomass and Bioenergy 194: 107635. https://doi.org/10.1016/j.biombioe.2025.107635.
- Vakalis, Stergios, Anargyros Georgiou, Konstantinos Moustakas, and Michail Fountoulakis. 2022. “Assessing the Effect of Hydrothermal Treatment on the Volatile Solids Content and the Biomethane Potential of Common Reed (Phragmites australis).” Bioresource Technology Reports 17: 100923. https://doi.org/10.1016/j.biteb.2021.100923.
- Xypolias, Panagiotis, Stergios Vakalis, Ioannis Daskaloudis, and Dimitrios F. Lekkas. 2023. “Hydrothermal Carbonization of Dry Anaerobic Digestion Residues Derived from Food and Agro-Wastes in Lesvos Island.” Energies 16 (12): 4619. https://doi.org/10.3390/en16124619.
- Yin, Chun-Yang, Mohanad El-Harbawi, and Zhong-Tao Jiang. 2023. "Life Cycle Assessment of Production of Hydrochar via Hydrothermal Carbonization of Date Palm Fronds Biomass" Materials 16, no. 20: 6653. https://doi.org/10.3390/ma16206653