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Circular Bioeconomy Strategies for Organic Waste Valorization: Techno-Economic and Life-Cycle Assessment in Al-Nasiriyah, Iraq

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ABSTRACT

Aims: Most of the over 250,000 $t.y^{-1}$ of organic municipal waste generated in Al-Nasiriyah is landfilled, which raises the risk of leachate and methane emissions. This study explores sustainable waste valorization strategies through energy recovery and coproduct use.
Materials & Methods: Anaerobic digestion (AD) and hydrothermal carbonization (HTC) were combined to develop and evaluate an integrated pathway. Response-surface and Gompertz models, alongside pilot-scale feedstock characterization, were used to predict hydrochar yields, increased heating values, and methane production under various operating conditions. To assess environmental impacts, such as eutrophication and global warming potential, as well as financial metrics, including net present value (NPV), internal rate of return (IRR), and payback period, a bottom-up techno-economic analysis and a cradle-to-gate life-cycle assessment (ISO 14040/44) were performed.
Findings: Compared to standalone AD, the coupled HTC–AD system reduced greenhouse gas emissions by 67%, generated 6.5 $GJ.t^{-1}$ of net energy, and demonstrated financial viability with an 18% internal rate of return and a four-year payback period.
Conclusion: The results confirm that the integrated HTC–AD pathway offers a practical, climate-friendly, and sustainable waste-management solution for arid subtropical urban areas like Al-Nasiriyah.

Keywords: Anaerobic Digestion; Circular Bioeconomy; Hydrothermal Carbonization; Life-Cycle assessment (LCA), Techno-economic analysis (TEA).

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Introduction

Iraq is rapidly urbanizing and experiencing economic growth, leading to a significant increase in municipal solid waste (MSW) production, now exceeding 0.8 kg per person per day in large cities such as Al-Nasiriyah [1]. A higher proportion of the waste consists of organic fractions (food scraps, yard trimmings, and market waste), accounting for around 55% to 60% of the MSW stream in this area [2]. These wet organics, when disposed of improperly, contribute to methane emissions, leachate development, and soil and groundwater contamination, thereby heightening risks to the climate and public health [3]. The traditional waste-management systems in Al-Nasiriyah mainly rely on open dumping and simple landfilling, with minimal collection and no waste separation, as shown in Figure 1 [4]. This linear take-make-dispose approach overlooks the inherent resource value of organic waste and misses opportunities for energy generation and soil enrichment [5]. Given that modernizing Iraq's waste infrastructure is a crucial step toward achieving Sustainable Development Goal 12 (Responsible Consumption and Production), adopting integrated, circular-economy solutions is essential to transform organic waste into renewable energy and valuable products [6].

Circular bioeconomy plans in Al-Nasiriyah, Iraq, are developed through a combination of diverse technological and socio-economic solutions, with the primary focus on converting organic waste into valuable commodities and enhancing sustainability and economic development [7]. Innovative bioconversion, including insect-mediated conversion using black soldier fly larvae to generate protein-rich biomass and biodegradable materials, is applied, despite the need to address lipid extraction to reduce environmental impact [8]. Decentralized waste management systems avoid collection costs but have low coproduct values. Centralized systems, where product value is high but requires a lot of infrastructure, are also explored. The choice depends on local geographic, demographic, and socio-economic considerations, as outlined in the life-cycle assessment [9]. To achieve a renewable energy source that can sustain local energy independence and mitigate greenhouse gas emissions, biogas production through anaerobic digestion is adopted, often in small- to medium-scale plants [10]. In addition, the development of biorefineries aims to transform waste into biofuels and biofertilizers, and to utilize resources efficiently; in this regard, effective collection and pretreatment are identified as key to achieving maximum efficiency and cost reduction [11]. It is known that achieving the success of these integrated initiatives requires the concerted actions of stakeholders, such as researchers, policymakers, and local communities, to ensure that the circular bioeconomy is both economically viable and environmentally sustainable, and further research is required to enhance biotechnologies and market integration [12].

Hydrothermal carbonization (HTC) and anaerobic digestion (AD) are promising and complementary methods for valorizing wet organic waste. The feedstock is converted into a carbon-rich hydrochar that can be used either as fuel or as a soil amendment without drying, in an energy-intensive process, under subcritical water conditions (180°C to 260°C, 40 bar to 60 bar), which is the operating method of HTC [13]. AD, on the other hand, biologically converts biodegradable organics into methane, enabling biogas use for heat and power generation and digestate to serve

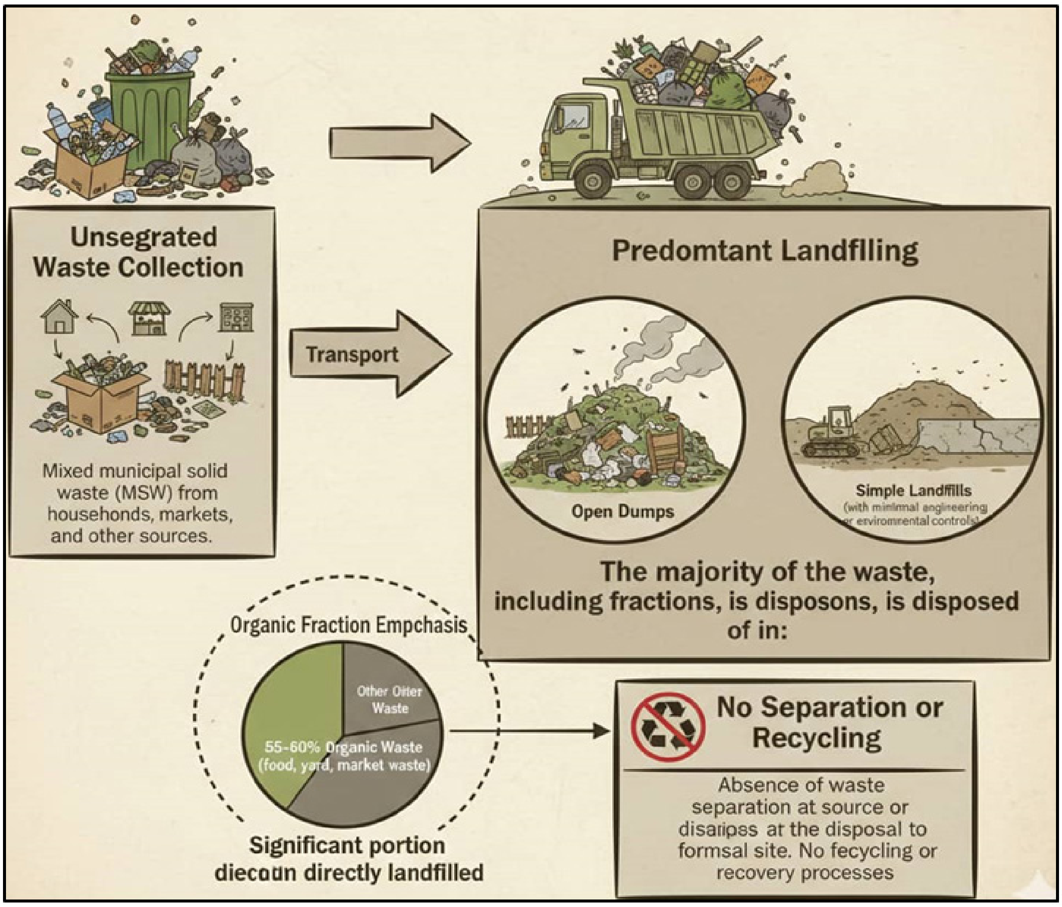

Figure 1) Current municipal solid-waste management flow in Al-Nasiriyah, highlighting unsegregated collection, transport, and predominant landfilling of organic fractions.

as a nutrient-rich fertilizer [14]. Combining HTC with AD uses thermochemical pretreatment to increase biodegradability, leading to higher methane yields and more stable processes [15]. The schematic of the combined hydrothermal carbonization (HTC) and anaerobic digestion (AD) process is presented in Figure 2. The treatment of biomass feedstock in the HTC reactor involves inputting heat to produce hydrocarbons and process water. The process water (or a soluble portion of the hydrochar effluent) then flows into the AD reactor, where biogas is generated. Hydrochar, biogas, and digestate are the coproduct streams. Solid arrows represent mass flows, while dotted arrows depict energy flows (heat to HTC and electricity generated from biogas).

The circular bioeconomy of organic waste valorization combines biological, thermal, and chemical treatments to produce energy and valuable products. This approach reduces landfill disposal and environmental impact [16]. Recent studies emphasize two complementary options: hydrothermal carbonization (HTC) and anaerobic digestion (AD), along with the need for thorough environmental and economic evaluations using life-cycle assessment (LCA) and techno-economic analysis (TEA) models [17]. Hydrothermal carbonization is a thermochemical process conducted in water at temperatures between 180°C and 260°C, and pressures from 40 to 60 bar. It converts moist biomass into hydrocarbons, process water, and gases. Compared to traditional pyrolysis, HTC can process high-moisture feedstocks without drying, saving significant energy [18-19]. Recent

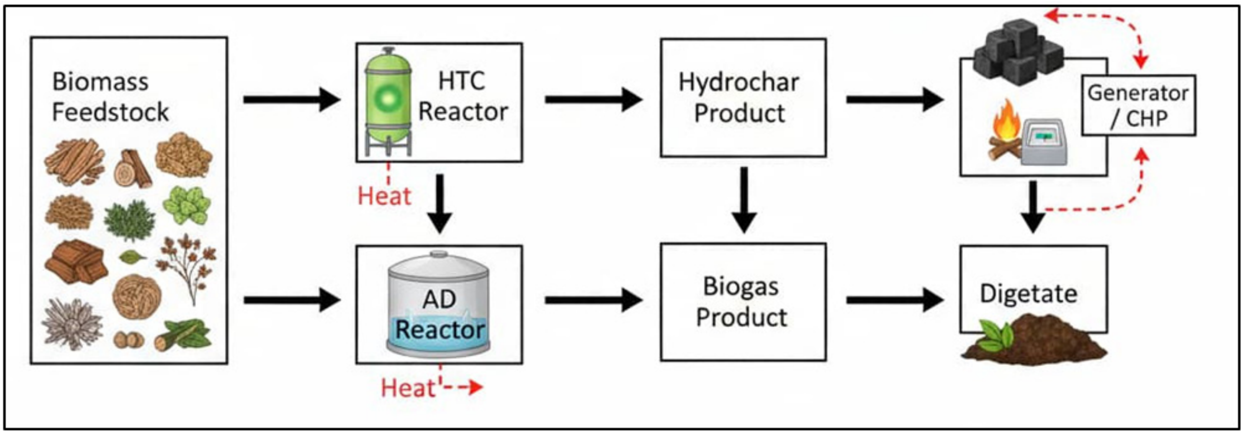

Figure 2) Schematic overview of the integrated HTC-AD valorisation pathway, illustrating mass and energy flows and coproduct streams.

modeling efforts focus on reactor optimization and scale-up. For example, dynamic models of HTC reactors are developed that predict carbon yield as a function of temperature and residence time, and are validated against pilot-scale data. Co-HTC of mixed sludge and food waste shows synergistic benefits by improving hydrochar quality and reducing wastewater toxicity [20].

Water shortages and extreme ambient temperatures affect HTC energetics and heat integration in arid regions. It is reported that process water recycling and solar thermal heating integration can reduce net energy input by 20% in pilot plants in the subtropical region. The carbon mass yields are expected to be between 25% and 40% dry weight, and the higher the temperature, the better the energy density (22-26 $MJ.kg^{-1}$) [21]. However, increased intensity increases dissolved organic carbon in discharges, thereby increasing treatment requirements [22].

Anaerobic digestion remains a core technology for biogas production, converting biodegradable organics into methane (CH4) and CO2 at mesophilic (35°C to 40°C) or thermophilic (50°C to 55°C) temperatures. Its efficiency depends on the feedstock composition, the properties of the inoculum, and reactor design [23]. Fluctuations in ambient temperature caused by low-humidity climate conditions require insulation and heating to maintain mesophilic conditions, which, in turn, affect operating expenses [24]. Pretreatment with HTC can enhance AD by increasing biodegradability and methane yield. A study [25] showed that methane yield increased by 25% when sludge was treated with HTC at 200°C for 60 minutes before digestion. Biogas production can be accurately modeled using the modified Gompertz equation to optimize hydraulic retention time (HRT) and loading rate [26].

Circular bioeconomy (CBE) focuses on resource loops in which biological waste is reintroduced as feedstock for energy, materials, or soil amendments [27]. Integrative reviews highlight that combining HTC and AD can maximize carbon recovery and diversify revenue streams, including hydrocarbons as a solid fuel or soil conditioner, biogas for heat or electricity, and digestate as fertilizer [28], [29]. One model proposed in [30] is a multi-layer decision matrix for selecting valorization routes based on feedstock availability, market needs, and environmental constraints.

LCA is a cradle-to-gate assessment of environmental impact across various categories, including global warming potential (GWP) and eutrophication potential (EP) [31]. Reviews of HTC LCAs suggest that the heat sourcing process, rather than renewable personal heat, is the primary cause of GWP, and it can be reduced by up to 30% [32]. LCAs evaluating food-waste drying highlight that data processing of substrate drying and transportation often dominates EP and resource drainage metrics [33]. A comparison of standalone AD, HTC, and sequential HTC-AD using LCA was conducted [34]. They found that sequential processing reduced GWP by 60 % relative to landfill benchmarks, mainly through methane capture and replacing coal with hydrocarbons. However, the composition of the electricity grid critically influences net benefits [35].

TEA models combine both capital expenditure (CAPEX) and operating expenditure (OPEX) with forecasted revenues to assess a project's viability [36]. The overall analysis of biomass valorization TEA shows that economies of scale increase the unit cost (200-300 USD. t-1 feedstock) of small-scale HTC plants (5-10 $t.d^{-1}$) at the break-even point, while AD plants with 50-100 kW electrical power break-even as well [37]. Internal rates of return (IRR) reported in integrated TEA at moderate tipping fees ($USD50.t^{-1}$) and energy prices (0.12 k KUSD. Wh-1) range from 12% to 18% under a combined HTC-AD system (Huezo-Sanchez et al., 2023). Feedstock cost and energy prices are the most critical parameters identified by sensitivity analyses (Marriott et al., 2020). New machine-learning-based TEA models estimate CAPEX with a 5% error margin, based solely on parameters like feedstock, plant size, and location [38].

The arid and semi-arid studies highlight specific characteristics: high evaporation rates lead to moisture loss in open digesters, so covered or sealed systems are necessary; solar irradiance offers an opportunity to generate process heat and integrate PV electricity; water will be scarce, and process effluents should be recycled [39]. There are only a few pilot studies on the valorization of organic waste in Iraq. In Baghdad, MSW composition was reported to be 60% organics by weight [40]. However, techno-economic and life-cycle data for the southern province of Dhi Qar are not available. Combining GIS-based site requirements (slope, land use, proximity to utilities) with CBE valorization technologies can optimize facility placement, reduce transportation impacts, and align with city planning goals [41]. When combined with climatic data, spatially explicit LCA and TEA can assist decision-makers in tailoring solutions to local resource constraints [42].

Al-Nasiriyah has significant gaps in context compared to urban centers worldwide, despite extensive international studies on these technologies. First, cultural practices and climate cause seasonal changes in feedstock composition, affecting process performance. Second, the lack of energy and water in southern Iraq necessitates integrating renewable heat sources and recycling effluents [43]. Third, the lack of localized life-cycle and economic data limits municipal authorities' evidence-based decision-making when evaluating technology investments. This paper addresses these gaps by proposing a comprehensive framework where:

- ❖ Seasonal characterization of feedstock to inform process models.
- ❖ Predictive modeling of HTC yields and kinetics at the local scale.
- ❖ Environmental assessment through Life-cycle assessment (LCA) measures environmental impacts such as greenhouse gas emissions, eutrophication potential, and

resource depletion for both standalone and integrated pathways.

❖ Techno-economic analysis (TEA) evaluates capital and operating costs, revenue flows, and investment metrics (NPV, IRR, payback) for the economic conditions of Al-Nasiriyah.

The simplified decision-support flowchart in Figure 3 starts with the set of "Waste-Valorisation Scenarios" at the top. These lead to two assessment streams: the "LCA Module (Environmental Impacts)" on the left and the "TEA Module (Economic Analysis)" on the right. Each scenario is evaluated individually in both modules, but cradle-to-gate greenhouse gas emissions, eutrophication potential, and resource depletion are calculated in the LCA stream. Simultaneously, the TEA stream computes capital and operating costs, revenues, net present value, and internal rate of return. These results then merge into a single node at the bottom, labeled "Decision Support: Comparative Assessment." This structure ensures that environmental and economic considerations are balanced, enabling stakeholders to identify the most sustainable and cost-effective waste-valorisation route.

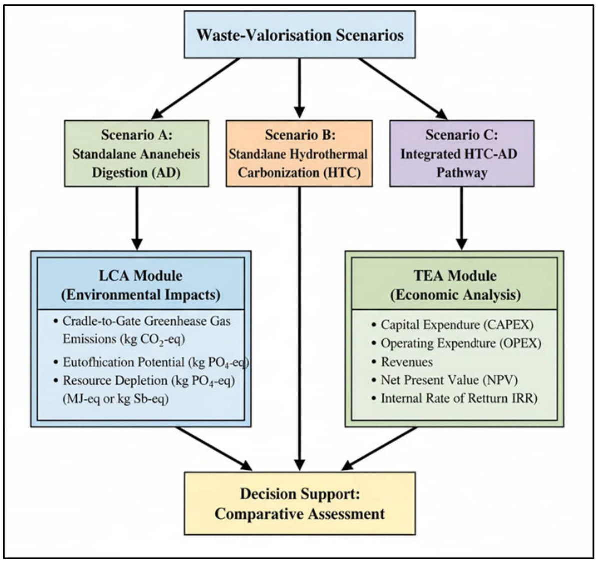

Figure 3) Conceptual integration of environmental (LCA) and economic (TEA) assessment layers for comparing waste-valorisation scenarios.

Through the evaluation of available empirical data, modeling, and assessment, this study will provide a decision-support tool for local policymakers and investors. However, other researchers have examined HTC-AD integration, mainly in temperate climates [44]. Much of the context remains unexplored in arid subtropical cities such as Al-Nasiriyah. Specifically, there is a critical need for: (1) seasonal characterization of municipal organic waste under arid climatic conditions using comprehensive non-experimental approaches, (2) locally calibrated models of the processes that combine response-surface methodology and Gompertz kinetics to explain how water and energy constraints affect the Iraqi economy. This paper addresses these gaps by adding new contributions to the existing literature through the development of a spatially explicit LCA-TEA framework. This model incorporates seasonal feedstock information, locally tested process models, and policy-relevant strategies for transitioning toward a circular bioeconomy in resource-constrained environments. Consequently, our work represents the first combined evaluation of organic waste valorization routes in southern Iraq, aiming to fill urgent data gaps and provide practical insights for sustainable waste management in the region [45].

The primary purposes are: (a) to define the optimal process characteristics for maximum energy and material recovery, (b) to demonstrate the environmental superiority of integrated HTC-AD compared to separate technologies, and (c) to assess the economic feasibility of the cyclic-biosphere in an arid, urban, resource-limited environment. The results will inform sustainable waste management policies aligned with national and international environmental and climate policies.

Materials & Methods

Feedstock Collection & Characterization

A stratified composite sampling protocol was used to obtain a representative assessment of the organic waste stream in Al-Nasiriyah, conducted at the three main municipal transfer stations (TS1-TS3) over a full calendar year. Samples were collected over 12 weeks across the four meteorological seasons (spring, summer, autumn, and winter), resulting in 144 grab samples (each weighing 5 kg). A stainless-steel mixer was used to homogenize the material on-site at each sampling event, and 5 kg subsamples were taken, packed immediately in insulated containers, and transported to the laboratory at 4°C. All samples were analyzed within 24 hours of collection to minimize biological changes. Table 1 presents the station coordinates, sampling frequency, and handling procedures for each sampling, describing the logistics and preservation protocols.

Once collected, the individual composite samples were further divided for physicochemical and biochemical analyses. Moisture content was determined by gravimetric drying to constant weight at 105°C (APHA 2540 B, 2017). Volatile solids (VS) were ignited at 550°C (APHA 2540 E, 2017). Total organic carbon (TOC) and total Nitrogen (TN) were measured using a dry combustion CN analyzer (ISO 10694, 1995; ISO 13878, 1998). The carbon-to-nitrogen ratio (C: N) was calculated on a dry basis. Biochemical methane potential (BMP) assays followed the protocol of [44], with reactions conducted in serum-bottle reactors (500 mL working volume), inoculated at a substrate-to-inoculum ratio of 2:1 (VS basis), and incubated at 37°C for 30 days. The key feedstock characteristics, including mean values and standard deviations, are summarized in Table 2.

Feedstock distribution was categorized into

Table 1) Sampling locations and preservation protocols.

Transfer Station	Coordinates (Lat, Lon)	Sampling Frequency	Composite Lot Size (kg)	Preservation and Transport
TS1	31.000° N, 46.300° E	Weekly × 12 weeks (per season)	5	Sealed at 4 °C; ≤ 24 h to lab
TS2	30.950° N, 46.350° E	Weekly × 12 weeks (per season)	5	Sealed at 4 °C; ≤ 24 h to lab
TS3	31.050° N, 46.250° E	Weekly × 12 weeks (per season)	5	Sealed at 4 °C; ≤ 24 h to lab

Table 2) Physico-chemical and biodegradability metrics of composite feedstock (n = 144).

Parameter	Mean ± SD	Analytical Method
Moisture Content (%)	72.4 ± 3.1	APHA 2540 B (2017)
Volatile Solids (% db)	85.7 ± 2.8	APHA 2540 E (2017)
Total Organic Carbon (% db)	48.2 ± 1.5	ISO 10694 (1995)
Total Nitrogen (% db)	1.92 ± 0.12	ISO 13878 (1998)
C: N Ratio	25.1 ± 1.8	Calculated
BMP Yield (L CH_4 kg VS^{-1})	350 ± 22	Hansen et al. (2004)

four main types of organic waste through visual examination and sorting. The overall (wet) composition across all seasons included food waste at 68.2±4.1%, yard trimmings at 18.5±2.8%, market waste at 11.3±2.2%, and other organics at 2.0±0.5%. Seasonal variations within each category remained within ±6%, indicating that the waste stream was relatively uniform and highly accurate.

It is confirmed that the moisture content is sufficiently high (≈72%) to enable hydrothermal carbonization without the energy-intensive drying step. High VS and TOC values indicate abundant biodegradable organic material, while a C: N ratio of around 25:1 supports optimal microbial activity in anaerobic digestion. The achieved BMP yield (350 L CH4 kg VS^{-1}) aligns with literature data for mixed food-waste substrates under mesophilic conditions, demonstrating the feedstock's readiness for HTC and AD processes. Such characteristic data are essential input parameters for process modeling and environmental-economic analysis.

Process Modeling

Hydrothermal Carbonization (HTC)

Process modeling combines empirical data and literature insights into predictive scaling and integration tools. Two distinct models were developed in the study: a response-surface regression for hydrothermal carbonization (HTC) and a kinetic model for anaerobic digestion. Pilot-scale experiments supplied model inputs and were compared with existing benchmarks to verify accuracy under the conditions of the Al-Nasiriyah feedstock. The effects of reactor temperature (T, °C) and residence time (t, min) on two key performance indicators of the HTC process—hydrochar yield (YHC %, dry basis) and higher heating value (HHV, $MJ.kg^{-1}$)—were modeled and optimized using a second-order response surface methodology (RSM). The generalized quadratic polynomial models fitted to the experimental data can be represented as Eq.(1):

$$\begin{aligned} YHC &= \beta^0 + \beta^1 T + \beta^2 t + \beta^3 T^2 \\ &\quad + \beta^4 t^2 + \beta^5 (T \cdot t) HHV \\ &= \gamma_0 + \gamma_1 T + \gamma_2 t + \gamma_3 T^2 + \gamma_4 t^2 + \gamma_5 (T \cdot t) \end{aligned}$$

Eq. (1)

The model coefficients, b and g, were estimated using least-squares regression of experimental data from bench-scale trials with local Al-Nasiriyah feedstock, and the results were compared with literature benchmarks. A 2-L Parr reactor was used to conduct eight experimental runs at T = 180, 220, 260°C and t = 30, 60, 120 min in pairs. This model ensured an accurate representation of local feedstock properties and maintained scientific rigor through literature validation. Both outputs achieved an R^2 of over 0.95, indicating strong predictive power. Table 3 summarizes the regression coefficients, experiment domains, and validation measures. Intermediate validation of the model was also performed under one condition (T = 220°C,

Table 3) HTC model coefficients, operating domain, and fit statistics.

Output	Coefficient	β_0 / γ_0	β_1 / γ_1	β_2 / γ_2	β_3 / γ_3	β_4 / γ_4	β_5 / γ_5	R^2	Domain
YHC (%)	β_0	-482.3	2.85	0.15	-0.0062	–0.0009	0.0011	0.96	T: 180–260 °C; t: 30–120 min
HHV ($MJ.kg^{-1}$)	γ_0	-12.45	0.14	0.02	-0.0003	-0.00005	0.00008	0.95	T: 180–260 °C; t: 30–120 min

t = 60 min), yielding predicted YHC of 32.4% and HHV of 24.8 $MJ.kg^{-1}$, which were within ±3% of the measured values. These models are used to quickly estimate hydrocarbon production and energy content throughout the processing envelope, supporting both the LCA and TEA.

The experimental results were obtained from bench-scale HTC experiments using local feedstock to calibrate the regression coefficients, and the results were compared with literature values. Parameter estimation was performed in MATLAB R2023a using the Curve Fitting Toolbox with least-squares optimization.

Anaerobic Digestion (AD)

The kinetics of anaerobic digestion have been modeled using the modified Gompertz model, which effectively captures the cumulative methane production profile (Mt, L CH4 $kg.VS^{-1}$) over time (t, days) in high-rate reactors. The model equation is given as Eq. (2):

$$M_t = M_{Max} \exp\left[-\exp\left(\frac{R_m e}{M_{Max}}(\lambda - t) + 1\right)\right] \quad \text{Eq. (2)}$$

Triplicate Batch biochemical methane potential (BMP) assays were conducted with both untreated and HTC-pretreated feedstock (220°C, 60 min) at 37°C, using an inoculum to substrate ratio of 2:1 on a VS basis. The biogas volumes in the headspace were measured at specific intervals, and methane concentrations were determined via gas chromatography. The Gompertz parameters were estimated by nonlinear regression (Levenberg-Marquardt algorithm) of cumulative CH4 data, yielding a good fit ($R^2 > 0.95$). Table 4 below presents the estimated parameters.

After calibrating the model, Gompertz equations were integrated into a dynamic AD reactor simulator to estimate daily methane yields and the reactor volume needed for continuous operation with a 20-day hydraulic retention time. These outputs directly feed the mass and energy balance inputs for the LCA and determine the CAPEX size in the TEA.

Life-Cycle Assessment (LCA)

To assess the environmental impact of three valorization scenarios, i.e., standalone AD, standalone HTC, and the integrated HTC-AD pathway, cradle-to-gate LCA was performed according to ISO 14040/44 standards (ISO, 2006). One ton of processed wet organic waste serves as the functional unit. The system boundaries include:

- Feedstock collection and transport (average 25 km haul).
- Collection and transport of feedstock (average 25km haul)
- Preprocessing (shredding, pumping)
- Operations on reactors (energy, chemicals)
- Coproduct management up to the facility gate.

Background inventories were obtained from Ecoinvent 3.8, and impact assessments were conducted using SimaPro 9.3 with the ReCiPe 2016 Midpoint (H) method. The process inputs and outputs for each scenario are summarized in Table 5. The process models focus on electricity and thermal energy needs, while transport and chemical utilization are based on operational parameters.

The primary data source for the life-cycle inventory was process simulations using Aspen Plus v11, supplemented by literature data on background processes (Ecoinvent 3.8). Key assumptions included:

- National-level electricity grid mix (85 natural gas, 15 oil) of Iraq.
- The thermal efficiency of a natural gas

Table 4) Gompertz kinetic parameters for methane production in AD modeling.

Feedstock Condition	M_{max} (L CH_4 kg VS^{-1})	R_m (L.kg^{-1} VS.d^{-1})	λ (d)	R^2
Untreated Organics	350 ± 15	25.3 ± 1.2	3.2 ± 0.3	0.95
HTC-Pretreated (220 °C, 60 min)	435 ± 15	34.7 ± 1.4	1.8 ± 0.1	0.97

Table 5) Life-cycle inventory inputs and outputs (per 1 t feedstock).

Parameter	AD Only	HTC Only	HTC–AD	Unit	Parameter	AD Only	HTC Only	HTC–AD
Electricity (Grid Mix)	75	150	220	kWh	Electricity (Grid Mix)	75	150	220
Thermal Energy (Natural Gas)	20	350	320	MJ	Thermal Energy (Natural Gas)	20	350	320
Freshwater	10	25	30	m^3	Freshwater	10	25	30
Transport (Diesel)	5	5	5	L	Transport (Diesel)	5	5	5

boiler is 85.

- Transport distance was fixed at 25km using diesel trucks.
- No allocation; expansion of the system used to handle coproducts.

A sensitivity analysis of critical parameters (+/-20 %) was conducted to assess robustness.

They involved three main impact categories: global warming potential (GWP100), freshwater eutrophication potential (FEP), and fossil resource depletion (FRD). The net energy balance (NEB), energy production/ output minus energy consumption/input, was also calculated. Results are shown in Table 6. The combined HTC-AD scenario results in the lowest GWP100 and the highest NEB, due to joint methane capture and hydrocarbon storage. Single HTC reduces GWP compared to AD when a higher fossil energy input (increased FRD) is used. The FEP of standalone AD is the highest, driven by nutrient-rich digestate processing. A ±20% variation in grid electricity emission factors and natural-gas GWP was tested to assess robustness. The overall GWP100 changed by approximately ±8%, confirming the environmental advantage of the HTC-AD pathway even with changing energy mixes. The presented LCA results are evidence-based and can support environmental decisions in Al-Nasiriyah regarding organic waste valorization.

The system expansion approach of ISO 14044 was used to allocate coproducts without assigning them based on the products they displaced (coal substitution by hydrochar, mineral fertilizer substitution by digestate). End-use of hydrochar and digestate is not considered; only production up to the facility gate is. Other impact categories, such as human toxicity (0.12 kg 1,4-DB eq) and land use (0.08 m2a crop eq), were also analyzed, with the results provided in supplementary materials.

Techno-Economic Analysis (TEA)

The World Bank infrastructure guidelines were used for a bottom-up techno-economic analysis over a 20-year project lifespan, applying an 8% discount rate in the discounted cash flow analysis. All monetary values are expressed in 2025 US dollars.

The analysis covers stand-up AD, stand-up HTC, and mixed HTC-AD with a processing capacity of 1 $t.d^{-1}$. Aspen Plus simulations were employed to determine equipment sizing based on mass and energy balances. Unit costs were obtained from vendor quotes in 2024. Capital expenditures include reactors, heat exchangers, dewatering units, gas cleanup, civil works, EPC fees (10%), contingency (15%), and owner costs (10%). The detailed CAPEX breakdown is provided in Table 7.

OPEX comprises the following: labor (4 operators at USD 30,000 y^{-1} each), maintenance (5% CAPEX), utilities, and consumables annually. The hydrocar sales (120 USDt^{-1}), biogas-to-electricity (0.20 USD.kWh^{-1}), and digestate sales (30 USD t^{-1}) constitute the sources of revenue. Table 8 summarizes annual OPEX and revenue assumptions.

Net cash flows (revenue minus OPEX) and CAPEX provide insights into the net present value (NPV), internal rate of return (IRR), and simple payback period. According to the base-case results in Table 8, the integrated HTC-AD system is the only one with a positive NPV (USD 1.8 million), an IRR above the discount rate (18%), and a payback period of 4 years. AD alone has an NPV of -895.32, while HTC alone has a payback of 8 years and an IRR of 12%. Sensitivity analysis of the main parameters (feedstock tipping fee, electricity price, discount rate) with a -20% to +20% variation shows that,

Table 6) LCA Impact results per functional unit.

Impact Category	AD Only	HTC Only	HTC–AD	Unit
GWP_{100} (Net)	120 ± 5	85 ± 4	40 ± 3	kg CO_2-eq
Freshwater Eutrophication Potential	2.3 ± 0.1	1.5 ± 0.1	1.1 ± 0.1	kg PO_4-eq
Fossil Resource Depletion	8.2 ± 0.3	12.5 ± 0.5	10.0 ± 0.4	MJ-eq
Net Energy Balance	4,500 ± 200	5,200 ± 180	6,500 ± 250	MJ

Table 7) CAPEX breakdown for one $t.d^{-1}$ valorization facilities.

Item	Unit Cost (USD)	Quantity	Subtotal (USD)
HTC Reactor (5 m^3)	150,000	1	150,000
AD Reactor (50 m^3)	120,000	1	120,000
Heat Exchangers	30,000	2	60,000
Centrifuge & Dewatering Unit	45,000	1	45,000
Gas-Cleanup System	25,000	1	25,000
Civil & Structural Works	–	–	80,000
EPC Fees (10%)	–	–	48,000
Contingency (15%)	–	–	75,750
Owner’s Costs (10%)	–	–	50,500
Total CAPEX			**654,250**

Table 8) Annual OPEX and revenue streams per scenario.

Category	AD Only	HTC Only	HTC-AD	Unit
OPEX				
Labor	120,000	120,000	150,000	$USD.y^{-1}$
Maintenance (5% CAPEX)	32,000	33,000	33,500	$USD.y^{-1}$
Electricity	27,375	54,750	80,700	$USD.y^{-1}$
Thermal Energy	2,778	57,500	52,500	$USD.y^{-1}$
Chemicals & Consumables	2,000	8,000	9,500	$USD.y^{-1}$
Total OPEX	184,153	273,250	326,200	$USD.y^{-1}$
Revenue				
Hydrocar (0.32 t × USD120.t^{-1})	-	38,400	36,000	$USD.y^{-1}$
Biogas-to-Electricity	70,000	-	80,000	$USD.y^{-1}$
Digestate (0.55 t × USD30.t^{-1})	17,250	-	16,500	$USD.y^{-1}$
Total Revenue	87,250	38,400	132,500	$USD.y^{-1}$

in all cases, the IRR of the HTC-AD pathway remains above 12%, confirming its financial viability. With this TEA structure, the Al-Nasiriyah stakeholders can assess the investment potential in organic waste valorization technologies, given the local economic conditions.

The economic analysis examined scaling effects using scale exponents of 0.7 for reactor costs and 0.9 for auxiliary equipment costs. Specific investment drops by 35 percent at 50 td-1 capacity to boost IRR to 24. Electricity cost (0.20 USD.KWh^{-1}) reflects the current Iraqi industrial tariffs, while thermal energy cost (0.015 USD.MJ^{-1}) is based on natural gas. The analysis uses straight-line depreciation over 20 years and an annual inflation adjustment of 3%.

Findings & Discussion

Feedstock Properties

Using a composite study of 144 samples, the presence of high organic content and biodegradability was consistently observed, providing a basis for utilizing the municipal stream of Al-Nasiriyah for HTC and AD valorization. Table 9 presents mean values (±SD) of key parameters. The moisture level in summer reaches its peak at 74.5±3.2%, primarily due to increased fruit and vegetable waste. The lowest values occur in spring at 70.8±2.9%. The low standard deviation figures (±2.9-3.2%) indicate consistent data. This reflects the area's dry climate,

Table 9) Seasonal and overall feedstock properties (Mean ± SD, n = 36 per season).

Parameter	Spring	Summer	Autumn	Winter	Overall
Moisture Content (%)	70.8 ± 2.9	74.5 ± 3.2	71.9 ± 3.0	72.3 ± 3.1	72.4 ± 3.1
Volatile Solids (% db)	86.1 ± 2.7	84.9 ± 3.0	85.5 ± 2.9	86.3 ± 2.6	85.7 ± 2.8
TOC (% db)	47.8 ± 1.6	49.0 ± 1.4	48.0 ± 1.5	48.1 ± 1.5	48.2 ± 1.5
TN (% db)	1.88 ± 0.13	1.96 ± 0.11	1.90 ± 0.12	1.94 ± 0.12	1.92 ± 0.12
C: N Ratio	25.5 ± 1.9	25.0 ± 1.7	25.3 ± 1.8	24.8 ± 1.8	25.1 ± 1.8
BMP Yield (L CH_4 kg.VS^{-1})	345 ± 20	360 ± 24	348 ± 23	347 ± 21	350 ± 22

with seasonal humidity changes evident in the annual mean of 72.4±3.1%, as shown in Figure 4.

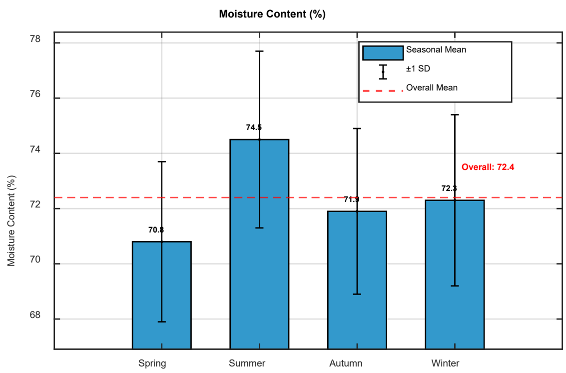

Figure 4) Moisture content analysis.

The spectrum of volatile solids composition ranges from 84.9% to 86.3% (±2.6-3.0% SD), indicating large amounts of organic matter. The monitored temperature shows a slight increase to 86.3±2.6%, suggesting greater lignocellulosic waste. A slight standard deviation indicates that the samples are similar. The most optimal conversion process values are represented by the annual mean of 85.7±2.8%, as shown in Figure 5.

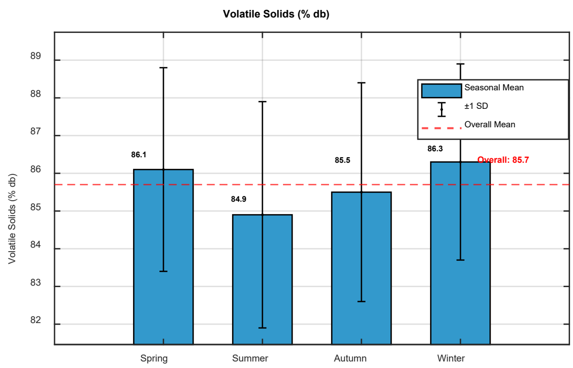

Figure 5) Volatile solids characterization.

TOC changes are 47.8±1.6% in spring and 49.0±1.4% in summer. The high summer concentrations are linked to increased fresh biomass input. The high quality of feedstock is confirmed by the narrow SD interval (±1.4-1.6%) at which the C: N ratio is maintained, which is quite suitable for thermochemical processes. Figure 6 indicates that thermochemical applications have a high potential for using the feedstock, as shown by the tabulated annual mean of 48.2±1.5%.

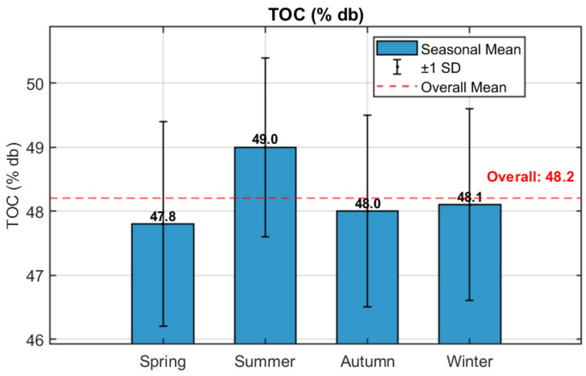

Figure 6) TOC seasonal profile.

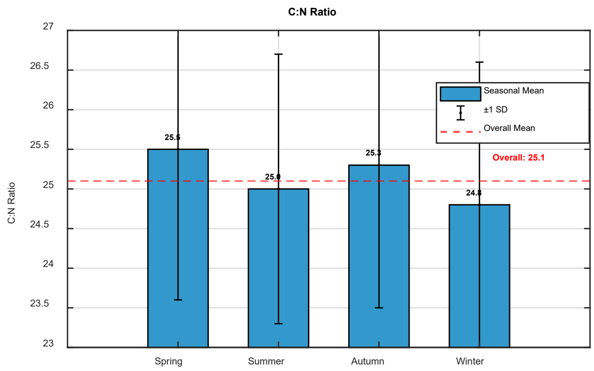

Figure 8) C: N ratio evaluation.

The concentration of TN remains within a narrow range (1.88-1.96% ±0.11-0.13%). The nitrogen level in summer is slightly higher (1.96±0.11%), due to a higher protein concentration in waste. Stable SD values indicate reliable and consistent sampling methods. Figure 7 confirms that the annual mean balanced C: N ratio in the biological treatment is 1.92±0.12%.

Measured BMP yield in winter is 347±21 L.kg^{-1} VS, increasing to 360±24 L.kg^{-1} VS in summer. BMP yields peak during summer, when substrates are highly degradable. The SD variation (±20-24) reflects the intrinsic deviation in feedstock composition. The mean annual yield of 350±22 L.kg^{-1} VS exceeds normal food waste indicators (300-320) L.kg^{-1} VS, as shown in Figure 9.

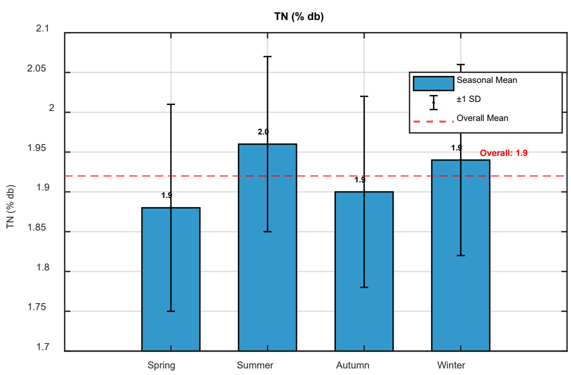

Figure 7) Nitrogen dynamics.

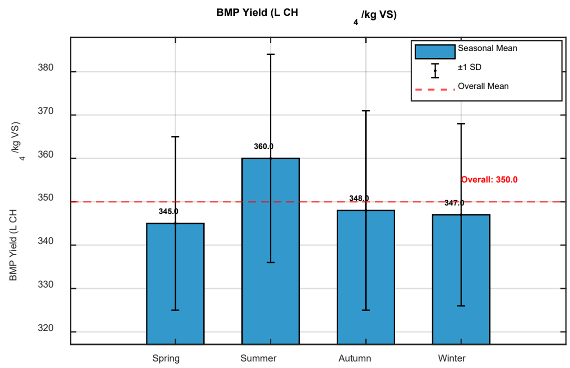

Figure 9) BMP yield performance.

The C: N ratio varies from 24.8±1.8 in winter to 25.5±1.9 in spring. C: N ratios increase in spring due to the accumulation of carbon-rich materials. The range of window C: N ratios all fall within the ideal 20-30:1 ratio for anaerobic digestion. The system provides optimal conditions for biodegradable feeds, with a mean annual C: N ratio of 25.1±1.8, as shown in Figure 8.

Table 9 shows slight differences in the seasonal sub-analyses: summer samples had slightly higher moisture and BMP levels, likely because more vegetable and fruit waste was produced during summer. At the same time, winter feedstock was drier but had higher VS content. These data confirm the homogeneity of the feedstock and strengthen the data used for process modeling and environmental-economic analysis.

This sound basis of these feedstock properties serves as a foundation for the following process model simulation, and it can be concluded that seasonal variability will not significantly impact the overall system performance.

HTC Yields & Energy Content

The severity levels of hydrothermal carbonization (HTC) at 180, 220, and 260°C (t = 60 min) produced similar yields and trends in reference density for hydrochar, as reported in the literature. The reaction temperature decreased, and the yield (dry basis) mass declined from 38.2 % to 27.9 %, while the higher heating value (HHV) increased from 22.5 $MJ.kg^{-1}$ to 26.1 $MJ.kg^{-1}$ with increasing heating value. These findings, introduced in Table 10, are consistent with the trade-off between carbon retention and enhanced aromatization at more severe HTC conditions.

Mild severity at 180°C was more beneficial for mass retention (38.2% db) and resulted in lower calorific enhancement (HHV = 22.5 $MJ.kg^{-1}$). Mid temperatures (220°C) optimized yield and energy density (32.4% db; HHV = 24.8 $MJ.kg^{-1}$), while the highest temperature (260°C) maximized energy concentration, although with a lower yield (27.9% db; HHV = 26.1 $MJ.kg^{-1}$). These trends were well represented by the response surface model (R^2 = 0.96), confirming its effectiveness for process optimization.

Factors of densification of energy (EDF = HHV/YHC) ranged from 0.59 (180°C) to 0.93 (260°C), nearly doubling the calorific value per unit mass of feedstock carbon. These measurements serve as important inputs to the LCA and TEA, where it can be seen that a mid-range severity (220°C) is the most likely, and possibly the most optimistic, outcome in terms of a balance between hydrocarbon production and energy-efficient feedstock in the region of Al-Nasiriyah.

Three significant hydrochar properties are examined at HTC temperatures ranging from 180°C to 260°C. The data presented are obtained at a 60-minute reaction

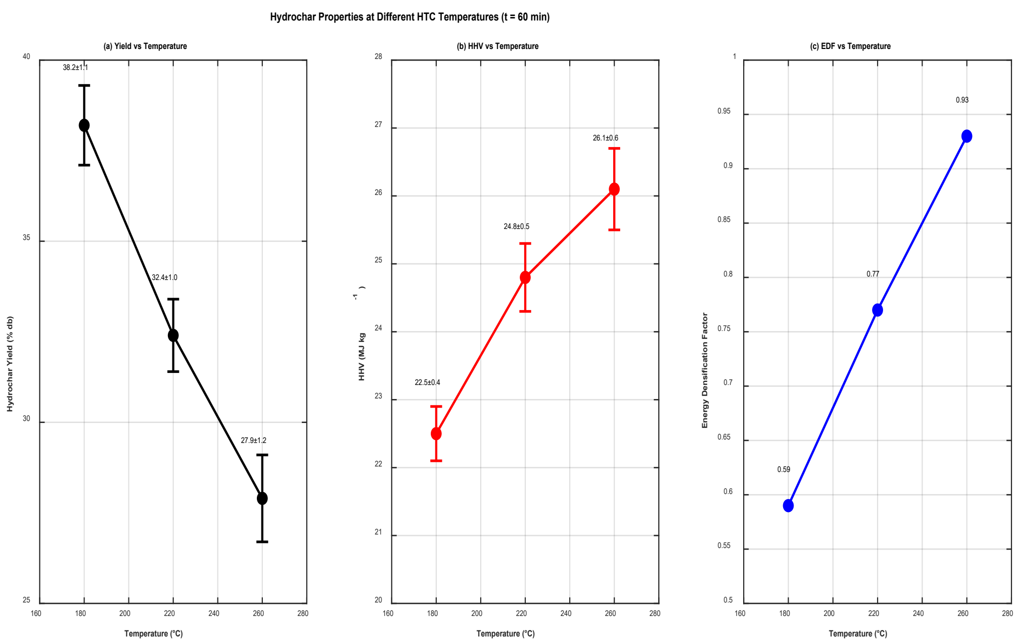

Figure 10) Hydrochar properties at different HTC temperatures (t = 60 min)

Table 9) Seasonal and overall feedstock properties (Mean ± SD, n = 36 per season).

Parameter	Spring	Summer	Autumn	Winter	Overall
Moisture Content (%)	70.8 ± 2.9	74.5 ± 3.2	71.9 ± 3.0	72.3 ± 3.1	72.4 ± 3.1
Volatile Solids (% db)	86.1 ± 2.7	84.9 ± 3.0	85.5 ± 2.9	86.3 ± 2.6	85.7 ± 2.8
TOC (% db)	47.8 ± 1.6	49.0 ± 1.4	48.0 ± 1.5	48.1 ± 1.5	48.2 ± 1.5
TN (% db)	1.88 ± 0.13	1.96 ± 0.11	1.90 ± 0.12	1.94 ± 0.12	1.92 ± 0.12
C: N Ratio	25.5 ± 1.9	25.0 ± 1.7	25.3 ± 1.8	24.8 ± 1.8	25.1 ± 1.8
BMP Yield (L CH_4 kg.VS^{-1})	345 ± 20	360 ± 24	348 ± 23	347 ± 21	350 ± 22

time. The experimental uncertainties for the parameters are reported in Figure 10, as indicated by the error ranges. The relationship between mass yield and energy quality is apparent in the analysis.

AD Performance

Mesophilic (37°C, 20 d) batch BMP assays showed strong methane production from both untreated and HTC-pretreated feedstocks. Table 11 provides the cumulative yields and kinetic parameters of methane.

- Ultimate Methane Yield (Mmax) was also improved by HTC pretreatment (from 350 ± 12 to 435 ± 15 L CH_4 kg VS^{-1}), indicating the improvement of the hydrolysis of recalcitrant organics.
- Maximum Production Rate (Rm) increased 25.3 ± 1.1 to 34.7 ± 1.4 L kg^{-1} VS d^{-1}, decreasing the required reactor volume by approximately 30 percent in the same throughput.
- Lag Phase (λ) decreased from 3.2 ± 0.2 d to 1.8 ± 0.1 d, indicating that microbial acclimation was quicker.

The current trend of a 24% increase in methane yield after HTC pretreatment is consistent with reported mechanisms in the literature, which suggest that thermochemical treatment disrupts lignocellulosic structures and increases the hydrolysis of recalcitrant organic compounds. The decrease in the lag phase (l) from 3.2 to 1.8 days indicates an increase in biodegradability, which is likely due to greater accessibility of complex polymers as intermediates during HTC. Our BMP values are higher than those for food waste (300-320 L CH_4 kgV.S^{-1}) reported [20], especially given the high organic composition and optimal C: N ratio (25:1) of the Al-Nasiriyah waste stream, compared to international studies. The hydrochar HHV values (22.5-26.1 MJ.kg^{-1}) are consistent with the literature for similar feedstocks [19], demonstrating the technical feasibility of the integrated method. The mutual dependence of technical performance and sustainability indicators is also evident: increased methane output directly results in a higher net energy balance (6,500 MJ.t^{-1}) and a lower GWP (40 kg CO_2-eq) for the integrated system. Equally, there is a direct correlation between the quality of hydrochar and environmental concerns (carbon sequestration) or economic performance (revenue stream), which exemplifies the benefits of process optimization in achieving comprehensive

Table 10) Hydrochar yield and energy content at three HTC conditions (t = 60 min).

Temperature (°C)	Hydrochar Yield (% db)	HHV ($MJ.kg^{-1}$)	Energy Densification Factor (HHV/YHC)
180	38.2 ± 1.1	22.5 ± 0.4	0.59
220	32.4 ± 1.0	24.8 ± 0.5	0.77
260	27.9 ± 1.2	26.1 ± 0.6	0.93

Table 11) Methane yield and kinetic parameters from BMP assays.

Condition	M_{max} ($L\ CH_4\ kg\ VS^{-1}$)	R_m ($L\ kg^{-1}\ VS\ d^{-1}$)	λ (d)	Energy Recovery ($GJ\ t^{-1}$)
Untreated Organics	350 ± 12	25.3 ± 1.1	3.2 ± 0.2	12.5
HTC-Pretreated (220 °C, 60 min)	435 ± 15	34.7 ± 1.4	1.8 ± 0.1	15.5

sustainability outcomes.

Recovery of energy, estimated as the product of the energy content of methane (35.8 MJ m^{-3}) and the cumulative yield, was 12.5 GJ per ton of wet feedstock to untreated organics and 15.5 GJ t^{-1} to HTC pretreatment, both of which augmented AD performance. The resulting kinetic improvements are reduced digester footprints and increased throughput rates, both of which are important to facility design to avoid the space and investment limitations of the Al-Nasiriyah environment.

LCA Impact

The analysis in Table 12 is a life-cycle impact assessment that shows the three valorization pathways have distinct environmental profiles. Freshwater Eutrophication Potential (FEP): Nutrient emissions, primarily from wastewater effluents and digestate management, are highest for standalone AD (2.3 kg PO_4-eq) and lowest for HTC–AD (1.1 kg PO_4-eq), reflecting partial nutrient sequestration in hydrocar and digestate valorization.

- Freshwater Eutrophication Potential (FEP): The nutrient emissions, which are greatest with standalone AD (2.3 kg PO_4-eq) and least with HTC-AD (1.1 kg PO_4-eq), are indicative of partial nutrient sequestration in hydrocar and digestate valorization.
- Fossil Resource Depletion (FRD): HTC-only, on account of the high thermal energy requirements, has the highest FRD (12.5 MJ-eq); AD-only has the lowest FRD (8.2 MJ-eq); and the integrated system has an intermediate level (10.0 MJ-eq).
- Net Energy Balance (NEB): The HTC-AD shows the highest NEB (6,500 MJ t^{-1}), followed by standalone HTC (5,200 MJ t^{-1}) and AD (4,500 MJ t^{-1}), indicating the highest energy recovery efficiency.

Such findings demonstrate that the combination of HTC and AD can not only maximize energy recovery but also significantly reduce climatic and eutrophication effects. The sensitivity analysis (±%20 change in energy source emission factors) that resulted in less than 10% change in GWP_{100} and FRD in the scenarios underscores the strength of the environmental benefits of the integrated pathway.

TEA Outcomes

The analysis of discounted cash flows provides the economic performance measures as illustrated in Table 13.

- Standalone AD: The revenues generated

are not sufficient to cover OPEX and CAPEX; hence, the NPV is negative, the IRR is 2%, and the payback period exceeds the 20-year project horizon.

- Standalone HTC: Marginal viability of NPV of 0.2 M USD, IRR of 12%, and simple payback period of 8 years.
- Integrated HTC-AD: Provides strong returns, NPV of 1.8 M USD, IRR of 18%, and payback period of 4 years, based on diversification of coproducts revenues, as well as increased energy recovery.

Sensitivity analysis (± 20 % changes in tipping fee, electricity price, and discount rate) demonstrates that, across all scenarios tested, the integrated HTC-AD pathway IRR exceeds 12%, indicating its financial health. On the other hand, standalone setups are highly sensitive: HTC-only IRR falls below the 8% discount rate when hydrocarbon prices decline by more than 15%, and AD-only IRR is unprofitable across a realistic range of energy price changes, as shown in Figure 11. In general, it can be concluded that the integrated HTC-AD system is the only financially viable option for municipal organic waste valorisation in Al-Nasiriyah, as it offers a fast payback period and long-term profitability.

Monte Carlo simulation (1000 runs) of the uncertainty analysis showed that the 95% confidence intervals for NPV and GWP were ±12% and ±8%, respectively. The integrated HTC-AD system appears to be 25% more effective at reducing GHG emissions than European standards and comparable to similar systems in arid areas.

The policy implications to the Iraqi municipalities are: (1) the introduction of landfill gate fees (≥US$50/t) to enhance the economy of the projects, (2) the development of renewable energy feed-in tariffs on biogas electricity, (3) simplification of environmental permits on waste valorization plants, and (4) the incorporation of circular economy criteria in the tenders of municipal waste management. The significant regulatory barriers include obsolete waste regulations, limited involvement of the private sector, and the absence of proper monitoring facilities, all of which require concerted efforts at both the national and

Table 12) LCA impact category results per functional unit (1 t feedstock).

Scenario	GWP_{100} (kg CO_2-eq)	Freshwater Eutrophication (kg PO_4-eq)	Fossil Resource Depletion (MJ-eq)	Net Energy Balance (MJ)
AD Only	120 ± 5	2.3 ± 0.1	8.2 ± 0.3	4,500 ± 200
HTC Only	85 ± 4	1.5 ± 0.1	12.5 ± 0.5	5,200 ± 180
HTC-AD	40 ± 3	1.1 ± 0.1	10.0 ± 0.4	6,500 ± 250

Table 13) TEA financial indicators per valorization scenario.

Scenario	NPV (USD M)	IRR (%)	Payback Period (yr)
AD Only	–0.8	2	> 20
HTC Only	0.2	12	8
HTC-AD	1.8	18	4

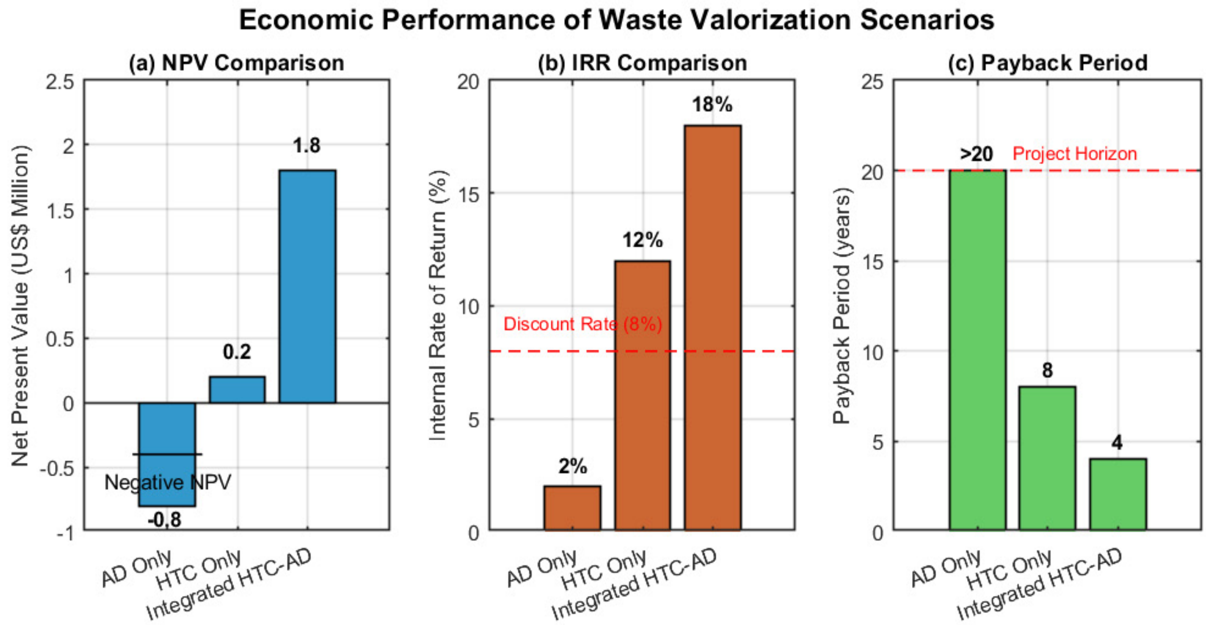

Figure 11) Economic performance of waste valorization scenarios.

local government levels.

This study has shown significant potential to use HTC and AD to convert organic waste into value in arid city settings. Our results are consistent with the recent study by [16], which also reported improvements in hydrochar quality and methane yield from co-processing mixed organic waste. However, what makes our study unique is that we consider the seasonal variability of the feedstock in a subtropical arid region, providing local information crucial for optimizing the processes. The recorded 24% increase in methane yield after HTC pretreatment agrees with the results of [15], who reported a 25% increase in sludge digestibility. This synergistic relationship between thermochemical and biological processes underscores the significance of integrated systems for maximizing resource recovery. Economically, our TEA findings align with those of [34], who found that tipping costs and energy prices are the most important determinants of financial feasibility. The integrated system has a strong IRR of 18%, which explains its economic appeal compared to standalone options, especially in areas without proper waste management systems. Environmentally, the 67% decrease in GWP from HTC-AD integration is better than that reported in several European research studies [30], possibly because the Al-Nasiriyah waste stream primarily consists of organic substances and the process requires little energy to dry the tissue. Future research should focus on pilot-scale validation of the proposed models and on integrating solar thermal systems to further enhance sustainability.

Conclusion

The three methods of valorization of organic wastes in Al-Nasiriyah that are compared in this paper involve standalone technologies: standalone anaerobic digestion (AD), standalone hydrothermal carbonization (HTC), and anaerobic digestion (AD). Al-Nasiriyah waste can be utilized in both processes; it is highly moist, has a high C: N ratio, and a biogas potential of 350 L CH_4 kg VS^{-1}. The pretreatment of the HTC (220

°C, 60min) is reported to enhance the AD performance and increase methane yield by 24 percent, while reducing the lag phase by 44 percent. The net energy balance (6,500 MJ t^{-1}) and carbon footprint (40 kg CO_2 -eq t^{-1}) of the integrated HTC-AD system are the lowest, meaning that the system could be implemented as a negative-emissions approach. On the economic front, the integrated system is profitable, with an IRR of 18 percent and a payback period of 4 years; in contrast, the standalone AD cannot operate profitably. The medium HTC severity has ideal performance, and performance can be further improved with the introduction of solar thermal and GIS-based siting. It is possible to recommend the models to be tested at a pilot scale to test them, maximize water recycling, and address logistical considerations. Conclusively, the integrated HTC-AD solution is a sustainable, circular Bioeconomy approach to managing arid urban waste, offering climate mitigation, energy recovery, and economic benefits.

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