Urine as a Renewable Resource: Pathways for Hydrogen, Methane, and Biocrude Production – A Review

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***Abstract*—Urine, a plentiful waste product high in nitrogen, is showing promise as a feedstock for clean energy and nutrient recovery. The latest developments in urine-to-fuel pathways, such as hydrothermal liquefaction of organics, microbial fuel cells, electrochemical hydrogen generation, and catalytic methanation, are compiled in this review. Energy efficiency, environmental advantages, and the possibility of integration with sanitation systems are highlighted by comparative analyses. The evaluation also looks at life-cycle and techno-economic viewpoints, suggesting that scalable solutions could have positive climate effects. Though durability, fouling, and social acceptance are still issues, new findings indicate that integrated urine valorization can help achieve the objectives of the circular economy.**

***Index Terms*—urine valorization; urea electrolysis; hydrogen; methanation; microbial electrochemical systems; hydrothermal liquefaction; struvite; TEA; LCA**

1 INTRODUCTION

Approximately 2% of human urine, together with nitrogen, phosphorus, salts, and organic components, is generated daily on average at a rate of 1.5 L per person. Urine, which has historically been considered a waste, is actually a nitrogen-rich, renewable stream that may be used to make fertilizer and fuel. Recent developments show its potential for producing biocrude, methane, and hydrogen. This review outlines recent scientific findings, points out difficulties, and makes recommendations for future directions.

1.2. Need Of Study:

Exploration of unconventional resources is urgently needed due to the rising demand for renewable energy on a worldwide scale and growing concerns about wastewater management. A significant source of nitrogen, carbon, and phosphorus molecules, human urine is generated in enormous amounts every day and is sometimes seen as trash. Urine greatly increases eutrophication, greenhouse gas emissions, and nutrient pollution if treatment is not received. Yet, in addition to fossil fuels and food-based biomass, renewable energy systems need other feedstocks. Urine valorization presents a novel option by facilitating the generation of hydrogen, methane, and biocrude while also tackling sanitary issues.

Crucially, these technologies may be included into decentralized sanitation infrastructure, providing fertilizer recovery and energy availability in areas where traditional treatment facilities are impractical. Despite developments in thermochemical, microbiological, and electrochemical techniques, there are still significant gaps in process integration, material durability, and socioeconomic acceptability. Combining scientific findings, highlighting the most promising avenues, and determining the areas that future research should concentrate on all need a comprehensive investigation. Therefore, this study offers a critical assessment of the state-of-the-art technologies, techno-economic viability, and environmental effects of urine-to-fuel conversion, pointing researchers and policymakers in the direction of useful implementation.

2. APPROACH TO LITERATURE SELECTION

2.0 Pathways for Urine-to-Fuel Conversion:

2.1 Electrochemical Approaches

Since direct urea electrolysis (DUEL) uses less voltage than traditional water electrolysis, it is a more energyefficient method of producing hydrogen. According to studies, hydrogen may be generated with promising efficiency at sub-1.5 V. Long-term durability and electrode fouling are still issues, though.

2.2 Microbial Electrochemical Systems

When fed urine, microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) have demonstrated low power densities (~1–2 mW cm^{-2}). In addition to treating wastewater, these systems may generate modest but valuable amounts of power, which makes them appealing for decentralized sanitation.

2.3 Thermochemical Routes

Biocrude oil in the range of 10–25 weight percent may be obtained by hydrothermally liquefying (HTL) concentrated urine organics, which are frequently co-processed with biomass such aquatic weeds. Although it has to be upgraded, this biocrude is a viable solution for storing liquid fuel.

2.4 Catalytic Methanation

Catalytic methanation can be used to convert urine processing off-gases that contain H_2 and CO_2 into methane. According to reported results, CH_4 selectivities above 90% may be achieved with catalysts based on Ni and Ru, and they have a great deal of promise for integration into the current biogas infrastructure

2.4.1 DUEL cell and electrodes

•Anode: Ni–Fe nanofoam (≈90% porosity) fabricated by template electrodeposition onto Ni mesh, polymer template removal, anneal; optional ultra-thin ALD TiO_2 passivation (5–10 nm).

•Cathode: Ni foam or stainless steel; Pt only for benchmarking.

•Reactor: Membrane-less, co-current tubular cell with gas-liquid separators and purge; modular stacking for scale-up.

•Operation: 25–60 °C; residence time 0.5–10 min; current 0.01–1.0 A cm^{-2}. Feeds: raw urine vs. diluted vs. synthetic urea.

•Analytics: Polarization curves, EIS, GC for $H_2/CO_2/N_2/CH_4$, NH_3 traps, Faradaic efficiency, 1000 h durability.

2.4.2 In-line catalytic methanation (novel)

- Catalyst: Ru/Al_2O_3 (benchmark) and Ni/Al_2O_3 (cost-down). 200–350 °C, 1–10 bar; space velocity tuned for ≥70% CO_2 conversion.
- Gas conditioning: NH_3 removal via acid scrub/adsorbent as needed; water knockout.
- Analytics: GC-FID/TCD for conversion/selectivity; 500 h stability tests.

2.4.3.Microbial electrochemical modules (supporting)

Single/dual-chamber MFCs/MECs with carbon-cloth anodes; metrics: power density, Coulombic efficiency, COD removal.

3. INTEGRATED ENERGY & RESOURCE RECOVERY

Multiple-vector energy recovery—hydrogen, methane, and biocrude—is made possible by combining electrochemical, microbiological, and thermochemical techniques. By creating fertilizers in addition to electricity, nutrient recovery via struvite precipitation and ammonia stripping further improves the system's circularity

4. TECHNO-ECONOMIC AND ENVIRONMENTAL PERSPECTIVES

Urine-derived hydrogen could be competitive when power costs are low (less than 10 kWh^{-1}), according to preliminary techno-economic analyses. Lifecycle studies indicate the possibility of lower nutrient pollution loads in effluent streams and net greenhouse gas reductions as compared to fossil fuel routes.

5. CHALLENGES AND RESEARCH GAPS

Despite promising outcomes, significant challenges remain:

- Electrode fouling and catalyst poisoning by ammonia.
- Scaling and maintenance of reactors under real-world conditions.
- Social acceptance of urine-derived fuels and fertilizers.
- Policy and regulatory frameworks for safe deployment.

6. CONCLUSIONS

Together, these routes create a **multi-vector energy recovery platform** that allows for the simultaneous generation of biocrude, methane, and hydrogen while recovering nutrients (such as struvite and ammonia salts). In addition to lowering greenhouse gas emissions and reducing nutrient contamination in receiving water bodies, this integration improves the techno-economic case overall.

The bottom line is that pee valorization is a viable, scalable method to turn a common waste stream into a variety of clean fertilizers and fuels, not just an academic curiosity. In the upcoming decades, urine-derived energy has the potential to play a significant role in low-carbon energy systems and sustainable sanitation with targeted study on durability, system integration, and practical piloting. There are still a number of significant obstacles to overcome before widespread adoption is possible, even with these encouraging scientific findings.

Fouling control, electrode longevity, and catalyst ammonia tolerance are technical obstacles that must be addressed. Simultaneously, a successful scale-up would require dependable technical solutions that can operate consistently under different feed conditions. Pilot-scale experiments combined with sanitary infrastructure are essential to verify technological feasibility and societal acceptance. Finally, clear regulatory standards and supportive policy frameworks will be needed to promote safe adoption, commercialization, and public trust.

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