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AI-Optimized Green Hydrogen Production from Whisky Distilling Waste: A Review

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Abstract: Whisky production generates large volumes of organic co-products, primarily pot ale and draff, that create disposal challenges but also offer a potential feedstock for renewable hydrogen. This review examines recent literature on converting whisky distilling wastes into green hydrogen through biological, thermochemical, and electrochemical routes, with emphasis on feedstock characteristics, process constraints, techno-economic performance, and life-cycle implications. It also considers how artificial intelligence and machine learning can support yield prediction, process optimization, fault detection, and real-time control. The literature indicates that hybrid configurations, especially wet-feed electrochemical approaches and integrated biological-electrochemical pathways, are promising for small and medium distilleries. Key barriers remain high moisture content, feedstock variability, impurity management, and limited standardized datasets for model development. The review concludes that robust data collection, digital twins, and AI-based optimization could accelerate practical deployment of distillery waste-to-hydrogen systems.[5]–[8]

Keywords— whisky distillery waste, pot ale, draff, biohydrogen, green hydrogen, machine learning, process optimization, electrolysis, techno-economic analysis.

1. Introduction

The whisky industry produces substantial quantities of co-products, mainly pot ale, spent lees, and draff, which are often used as animal feed or treated before disposal.[5] Growing decarbonization pressure and demand for low-carbon fuels have increased interest in valorising these residues for hydrogen production. Among the emerging options, electrochemical conversion of whisky waste streams has attracted attention because it may reduce or eliminate the need for energy-intensive drying.[5]

Recent studies show that distillery wastes can support multiple hydrogen pathways, including dark fermentation, anaerobic digestion followed by reforming, gasification, and electrochemical biomass conversion.[5], [7], [8] In parallel, AI and ML methods are being investigated to improve process design, predict performance, and support operation under variable feedstock and energy conditions.[6]–[8] This review brings together current knowledge on whisky distillery waste valorisation and frames AI as an enabling layer for optimized hydrogen systems.

2. Review Methodology

A targeted literature review was conducted on whisky distillery waste composition, biomass-to-hydrogen technologies, electrochemical hydrogen production, and AI/ML for process optimization.[5]–[8] Priority was given to peer-reviewed articles, technical reviews, and recent experimental work published from 2020 onward, with emphasis on studies relevant to distillery co-products and renewable hydrogen systems.[5], [7], [8] The objective was to identify technically credible pathways, practical constraints, and research gaps for future development.

3. Whisky Distilling Wastes

Whisky distilleries generate two principal co-streams: draff and pot ale.[5] Draff is the spent grain fraction remaining after mashing and is rich in lignocellulosic material, residual starch, and protein, making it a promising substrate for biochemical or thermochemical conversion. Pot ale is the liquid residue from distillation and typically contains soluble organics, proteins, acids, and salts, with high chemical oxygen demand and significant water content.

The composition of these co-products varies with feedstock, distillery operation, and process conditions, which affects conversion performance and technology choice.[5] In general, draff is more suitable for thermal or pretreated biochemical routes, while pot ale is better suited to wet-processing or biological treatment. This distinction is important because it determines whether drying, dilution, or pretreatment will dominate the process energy balance.

4. Hydrogen Conversion Pathways

A. Biological Pathways

Dark fermentation can convert fermentable components in distillery residues into hydrogen and volatile fatty acids under anaerobic conditions. This route is attractive because it can operate at relatively low temperature and pressure, but hydrogen yields are often modest and strongly dependent on substrate composition and operating stability.[6], [7] For that reason, dark fermentation is usually considered a front-end step rather than a complete solution.

Anaerobic digestion is another biological route that can process pot ale and, after suitable pretreatment, draff. The main product is biogas rather than hydrogen, but the biogas can be upgraded or reformed to generate hydrogen. This pathway may be useful where the priority is heat and energy recovery rather than direct hydrogen production, especially if the site already has digestion infrastructure.

B. Thermochemical Routes

Thermochemical conversion, especially gasification, can convert dried draff into syngas containing hydrogen and carbon monoxide. After gas cleanup and water-gas shift processing, the syngas can be upgraded to hydrogen.[7], [8] This route can offer high hydrogen yield, but it requires low-moisture feedstock and usually higher capital investment than biological options.

The main limitation is the energy demand for drying wet residues such as pot ale. That makes thermochemical processing more attractive for larger installations or for integrated systems where waste heat is available. In practice, this route is most compelling when distillery residues are consolidated and the plant can support gas cleaning, syngas conditioning, and carbon management.

C. Electrochemical Routes

Electrochemical biomass conversion is an emerging option for wet distillery streams. A key study demonstrated a two-stage electrolysis concept using draff and pot ale from the Isle of Raasay Distillery, with phosphomolybdic acid as the catalyst.[5] The study showed that draff and pot ale are the most promising co-products for hydrogen generation, while spent lees is not suitable because of its low biomass content.[5]

This route is especially interesting because it can process wet biomass without the severe drying penalties associated with thermal methods.[5] It also aligns well with renewable electricity supply, which makes it relevant for distilleries seeking decentralized low-carbon hydrogen production. However, the technology is still at an early stage and requires scale-up, durability testing, and realistic techno-economic analysis.

D. Hybrid Pathways

Hybrid systems may offer the best balance of efficiency and practicality. A biological pretreatment stage can reduce solids load or convert part of the carbon into intermediates, followed by reforming or electrochemical conversion to complete hydrogen production. Such combinations could be especially useful for small and medium distilleries that need flexible and modular systems.

Hybridization also improves robustness because each stage handles the feedstock fraction for which it is best suited. For example, wet fractions can be directed to electrochemical conversion, while solid-rich fractions can be diverted to thermochemical treatment. This process segregation may increase overall yield and simplify downstream handling.

5. AI and Machine Learning

AI and ML can strengthen every stage of a distillery-waste hydrogen system, from feedstock assessment to plant operation.[6]–[8] In feedstock characterization, regression and tree-based models can link moisture, COD, C:N ratio, and related analytical features to hydrogen yield. This helps operators choose whether a batch is better suited to digestion, gasification, or electrochemical processing.

In process monitoring, time-series learning and anomaly detection can identify instability, catalyst degradation, or membrane fouling early enough to reduce downtime.[6] In control applications, hybrid digital twins can combine physical models with data-driven corrections to support optimal scheduling under variable electricity prices and renewable power availability.[7], [8] This is particularly important for electrolysis-based systems that need to follow intermittent generation.

Machine learning is also useful for design-space exploration and techno-economic screening. Surrogate models can reduce the number of experiments needed to optimize pretreatment, catalyst loading, or process conditions. In the longer term, these tools can support plant-scale decision-making and improve the bankability of novel hydrogen pathways.[7], [8]

6. Techno-Economic and Environmental Issues

The feasibility of any route depends on hydrogen yield, feedstock moisture, capital cost, operating cost, renewable electricity availability, and local policy conditions. Thermochemical systems are generally more capital-intensive but can provide high hydrogen output at larger scale. Biological and electrochemical systems are more suitable for distributed use, but they must achieve acceptable performance and reliability to be economically viable.[7], [8]

Water content is a critical issue for whisky co-products, especially pot ale. High moisture strongly penalizes thermal routes, while wet electrochemical processing can reduce the need for drying.[5] Environmental performance also depends on life-cycle assumptions, including treatment of biogenic carbon, electricity source, pretreatment inputs, and possible methane leakage. For this reason, standardized life-cycle assessment and techno-economic analysis are essential before comparing pathways.[8]

7. Case Evidence

The most relevant distillery-specific experimental study to date is the RSC report on biomass electrolysis using whisky waste streams.[5] It demonstrated that draff and pot ale have the greatest potential for hydrogen generation and that spent lees has limited value as a feedstock for this purpose.[5] This provides a practical basis for discussing wet-feed electrochemical valorisation in distillery settings.

Broader renewable-hydrogen reviews also indicate that AI-driven optimization is gaining momentum across electrolysis, biomass gasification, and system integration.[6]–[8] These studies support the argument that AI should be incorporated not as an isolated feature but as part of the overall process architecture. That framing is important for making the review more coherent and more useful to readers.

8. Research Gaps

Several gaps remain before whisky distillery waste can be widely used for hydrogen production. First, there is a shortage of standardized datasets for feedstock composition, process performance, and operating conditions, which limits the transferability of AI models.[6] Second, feedstock variability across distilleries and seasons makes process control difficult.

Third, wet-feed electrochemical systems are promising but still low in technology readiness and need long-term validation.[5] Fourth, integration with real distillery energy demands has not been explored enough, especially for small and medium sites. Fifth, life-cycle and techno-economic results are not yet standardized enough to support direct comparison across pathways.[8]

9. Future Roadmap

Short-term progress should focus on pilot-scale data collection, feedstock characterization, and model development. Distilleries should monitor composition, yields, and operating conditions so that predictive ML models can be trained on real process data. At the same time, wet electrochemical conversion should be tested at relevant scale to establish performance limits.[5], [6]

In the medium term, hybrid digital twins should be developed for process optimization and scheduling. These models can be used to compare biological, thermochemical, and electrochemical routes under realistic cost and electricity scenarios. Standardized LCA and TEA frameworks should also be introduced so that technologies can be evaluated on a common basis.[8]

In the long term, integrated distillery demonstrations should combine waste handling, hydrogen production, and AI-based control. Industry-academic data consortia would help create better models and improve reproducibility. Such coordinated development would accelerate deployment and reduce the technical uncertainty associated with novel hydrogen pathways.

10. Conclusion

Whisky distillery wastes, especially pot ale and draff, are promising underused feedstocks for green hydrogen production.[5] Biological routes are relatively low-cost but usually lower-yield, thermochemical routes can deliver higher hydrogen output but require drying and greater capital investment, and electrochemical routes are particularly attractive for wet processing. Hybrid systems may provide the most practical near-term solution.

AI and ML can add value across feedstock selection, process monitoring, optimization, and techno-economic analysis.[6]–[8] The strongest case for future work is to combine robust data collection with pilot-scale validation and standardized assessment methods. If that happens, distillery waste-to-hydrogen systems could become a realistic component of decentralized low-carbon energy supply.

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