IMPLEMENTING ZERO-WASTE TECHNOLOGIES IN HEAVY PETROLEUM RESIDUE PROCESSING AND PATHWAYS TO ENHANCED INDUSTRIAL EFFICIENCY

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ABSTRACT: *This article reviews scientific approaches to zero-waste processing of heavy petroleum residues — vacuum residue, fuel oil, and tar — with emphasis on integrating mesoporous adsorbent-based separation and upgrading technologies. International studies on hydrocracking, delayed coking, solvent deasphalting, and pyrolytic carbon utilization are analyzed alongside Uzbek refinery context. Pathways to simultaneously increasing conversion yield and minimizing hazardous by-product generation are identified.*

Keywords: *heavy petroleum residues; zero-waste technology; mesoporous adsorbent; industrial efficiency; hydrocracking.*

INTRODUCTION

Global refinery operations face a mounting challenge: crude oil quality is declining as lighter reserves deplete, leaving behind progressively heavier

fractions that are difficult to convert and costly to dispose of safely. Vacuum residue, atmospheric residue, and tar fractions accumulate at the bottom of distillation columns and contain high concentrations of asphaltenes, resins, sulfur, nitrogen, vanadium, and nickel — components that deactivate catalysts, foul heat exchangers, and generate toxic effluents if not properly managed [1:1216].

The concept of zero-waste or near-zero-waste processing in this context does not mean eliminating all by-products; rather, it means redesigning refinery process chains so that every output stream — including solid residues and contaminated process streams — is converted into a usable material. Mesoporous adsorbents play a particularly strategic role in this paradigm: they can be deployed in pre-treatment stages to remove asphaltenes and metal-bearing compounds that would otherwise poison downstream catalysts, and they can themselves be manufactured from the pyrolytic solid residues generated within the same refinery loop, closing the material cycle [2:119686].

In Uzbekistan, the Bukhara and Fergana refineries are actively expanding deep-processing capacity, making the question of zero-waste integration both timely and practically urgent for national industrial strategy.

METHODOLOGY

Literature was identified through Scopus, Web of Science, and Google Scholar using the search terms "heavy oil residue zero waste processing," "vacuum residue hydrocracking efficiency," "mesoporous adsorbent asphaltene removal," and "refinery by-product valorization." Studies published between 2006 and 2024 providing quantitative process or materials data were prioritized. Six primary sources — five international peer-reviewed journal articles and one edited book chapter — were selected for the final analysis, following relevance screening and methodological quality assessment.

RESULTS: LITERATURE ANALYSIS

Integration of Conversion and Waste Minimization. Rana, Sámano, Ancheyta, and Díaz (2007), in a comprehensive process review published in Fuel, classified upgrading technologies into two strategic families: carbon rejection (visbreaking, coking, deasphalting) and hydrogen addition (hydrotreating, hydrocracking, aquaconversion) [1:1216]. Their analysis, covering over 150 industrial references, showed that carbon rejection processes are inherently wasteful in the zero-waste sense: they concentrate contaminants into a solid or semi-solid coke or asphalt phase that has limited further utility. Hydrogen addition processes, by contrast, convert virtually all feedstock into distillate products when properly integrated, with residual solids reduced to trace catalyst fines. The key barrier to universal adoption of hydrogen addition routes, however, remains their high capital cost and sensitivity to metal poisoning from vanadium and nickel present in vacuum residue [1:1219].

Prajapati, Kohli, and Maity (2021), reviewing slurry-phase hydrocracking in Fuel, identified this technology as the closest current approach to zero-waste residue conversion, with conversions reaching 70–95% and the dispersed catalyst system tolerating asphaltene-rich feeds that would deactivate fixed-bed units [2:119686]. The remaining solid fraction in slurry hydrocracking — typically 3–8 wt% of the feed — consists primarily of inorganic ash and spent catalyst particles, which can themselves be processed into mesoporous carbon-mineral composites under controlled pyrolysis conditions.

Role of Mesoporous Adsorbents in Zero-Waste Chains. Bandosz (2006), in the edited volume Activated Carbon Surfaces in Environmental Remediation, provided the physicochemical framework for understanding how mesoporous carbons function as selective adsorbents in industrial streams [3:38]. Their 2–50 nm pore channels accommodate asphaltene aggregates and metalloporphyrin complexes — molecules too large for microporous zeolites

— while their surface chemistry can be tuned through oxidation or functionalization to increase selectivity for specific contaminants [3:40]. When deployed upstream of hydrocracking reactors, mesoporous adsorbents protect expensive catalysts by removing the primary deactivating species before the feed enters the reactor, thereby extending catalyst life and reducing the frequency of costly regeneration shutdowns.

Marsh and Rodríguez-Reinoso (2006), in their monograph Activated Carbon, described how petroleum pitch and heavy tar fractions can be converted into activated carbons with BET surface areas of 500–1200 m^2/g and mesopore fractions exceeding 50% of total pore volume when carbonized at 700–850°C and subsequently activated [4:211]. This finding is directly relevant to a zero-waste refinery design: the coke or tar residue that emerges from a carbon-rejection unit can be fed into a carbonization furnace to produce the mesoporous adsorbent needed in the same refinery's pre-treatment stage, eliminating the need to purchase commercial adsorbent.

Comparative Technology Overview

Table 1. Key characteristics of heavy residue processing technologies in a zero-waste framework

Technology	Conversion (%)	By-product	Zero-waste potential	Mesoporous adsorbent role	Reference
Visbreaking	15–25	Fuel oil, SO_2	Low	Pre-treatment demetallization	[1:1216]
Delayed coking	25–40	Petroleum coke	Medium (coke valorized)	Coke → mesoporous carbon	[5:209]

Solvent deasphalting	20–50	Asphalt	Medium	Asphalt → adsorbent precursor	[1:1218]
Fixed-bed hydrocracking	50–90	Catalyst fines	Medium-High	Guard bed adsorbent required	[2:119686]
Slurry hydrocracking	70–95	Ash, spent catalyst	High	Spent solid → porous carbon	[2:119686]

Table 1 illustrates that slurry-phase hydrocracking paired with valorization of its solid residue into mesoporous adsorbent represents the most complete zero-waste pathway currently available at industrial scale.

DISCUSSION

The evidence reviewed here points to a coherent strategy for zero-waste heavy residue processing built around two interconnected loops. In the first loop, hydrogen addition technologies — especially slurry hydrocracking — maximize liquid product yield and minimize the mass of solid residue generated. In the second loop, the solid residue that does emerge is not disposed of but converted through pyrolysis and activation into mesoporous carbon adsorbents that are then recycled back into the process chain as guard-bed materials for catalyst protection and demetallization.

Munoz, Páez, and Ancheyta (2023) demonstrated that combining hydrotreating with delayed coking in a single integrated unit reduced residual sulfur content by over 80% relative to coking alone and cut solid coke yield by approximately 12 wt%, while producing a higher-quality coke suitable for subsequent activation [5:209]. This integration result supports the view that process-level design, not just materials-level innovation, is the critical lever for achieving zero-waste operation.

For Uzbekistan's refining sector, where both the Bukhara and Fergana facilities are undergoing capacity expansion, this integrated design philosophy offers a practical framework. Locally sourced heavy crude fractions with relatively low sulfur content — a known characteristic of Uzbek crude — would lower the hydrogen consumption required in the addition step, improving the economics of the integrated zero-waste approach.

CONCLUSION

Zero-waste processing of heavy petroleum residues is achievable through the deliberate integration of high-conversion hydrogen addition technologies with the in-house valorization of solid by-products into mesoporous adsorbent materials. Slurry-phase hydrocracking currently offers the highest conversion rates and the most tractable solid residue stream for downstream carbonization. Mesoporous carbons derived from refinery tar and coke fractions provide both the adsorption capacity and the pore geometry needed to function as protective pre-treatment adsorbents within the same process chain, closing the material cycle. Future research for Uzbekistan should focus on pilot-scale demonstration of this integrated loop using local crude fractions, with systematic characterization of the resulting mesoporous carbons using BET surface analysis and adsorption isotherm testing.

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