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VALORIZATION OF WASTE HEAVY HEXANE FRACTION FROM POLYETHYLENE PRODUCTION INTO OCTANE-BOOSTING ADDITIVES FOR AUTOMOTIVE GASOLINE: SYNTHESIS, PHYSICOCHEMICAL CHARACTERIZATION, AND TECHNO-ECONOMIC EVALUATION

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Abstract. The polyethylene production shop of the “Uz-Kor Gas Chemical” joint venture generates, as a technological residue, a waste heavy hexane fraction that is currently disposed of without added value and poses an environmental hazard. This work reports the conversion of this waste stream into octane-boosting additives for automotive gasoline through fractional distillation followed by catalytic oxidation, isomerization, alkylation, and esterification. Waste heavy hexane was separated into three temperature cuts (84–180, 180–220 and 220–247 °C) using an ARNS-1E fractionating unit, and each cut was characterized by gas chromatography–mass spectrometry (GC-MS, Agilent 5975C/7890A), which revealed a hydrocarbon group composition of 95.63 % paraffins, 0.96 % olefins, 0.35 % naphthenes and 3.07 % arenes, with individual components ranging from C_6 to C_{30}. Density, refractive index, kinematic viscosity, molecular weight and pour point increased monotonically with the boiling range of the fraction (density 708.3–740.9 kg/m³; kinematic viscosity 0.8423–1.6001 mm²/s; molecular weight 109.3–139.8 g/mol). Catalytic treatment of the three fractions with a $K_2Cr_2O_7$–H_2SO_4 oxidizing system over a Pt/Al_2O_3 catalyst (150–200 °C, 0.5–3 MPa, 90–180 min) produced three oxygenated additives, denoted E1, E2 and E3, with research octane numbers (RON) of 95, 97 and 99, respectively; Fourier-transform infrared (FT-IR) spectroscopy confirmed the appearance of carbonyl (1647–1750 cm^{-1}) and hydroxyl (3566–3736 cm^{-1}) absorption bands consistent with the formation of alcohols, ketones and ethers. Blending E1–E3 into AI-85 automotive gasoline at 5, 10 and 15 wt % raised the octane number from 85 up to 96.8 (motor method), the largest gain (11.8 units) being obtained with 15 wt % of E1. A process flow diagram and material balance were developed for a feedstock capacity of 730 t/y, and a techno-economic assessment showed

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an annual economic benefit of 2.744 billion UZS, a product profitability of 7.05 %, and a capital payback period of 23 months. The results demonstrate that waste heavy hexane, previously regarded as an unusable by-product, is a viable and economically attractive feedstock for import-substituting octane-boosting additives.

Keywords: waste heavy hexane; octane-boosting additive; catalytic oxidation; isomerization; gas chromatography–mass spectrometry; FT-IR spectroscopy; gasoline blending; techno-economic assessment.

Annotatsiya. “Uz-Kor Gas Chemical” qo‘shma korxonasining polietilen ishlab chiqarish sexi texnologik qoldiq sifatida og‘ir geksan fraksiyasi chiqindisini ishlab chiqaradi, u hozirda qo‘shimcha qiymat qo‘shmasdan utilizatsiya qilinadi va ekologik xavf tug‘diradi. Ushbu ishda ushbu chiqindi oqimini fraksiyonel distillash, so'ngra katalitik oksidlanish, izomerizatsiya, alkillash va esterifikatsiya qilish orqali avtomobil benzini uchun oktanni kuchaytiruvchi qo'shimchalarga aylantirish haqida xabar berilgan. Chiqindilarni og'ir geksan uch harorat kesilgan (84-180, 180-220 va 220-247 va 1e-1E fraksiyonlama birligidan foydalanib, va har bir kesilgan gaz xromatografiya bilan xarakterlanadi (GC-MS, Agilent 5975c/7890a), qaysi 95.63% parafinlar bir uglevodorod guruh tarkibini nozil, 0.96 % olefinlar, 0,35% naftenlar va 3,07% arenlar, alohida komponentlar bilan Cix dan Cividualgacha. Zichlik, sinishi indeksi, kinematik yopishqoqlik, molekulyar og'irlik va quyish nuqtasi fraktsiyaning qaynash oralig'i bilan monoton ravishda ortib bordi (zichlik 708,3–740,9 kg/m³; kinematik yopishqoqligi 0,8423–1,6001 mm²/s; molekulyar og'irligi 109,3–139,8 g/mol). (150-200, 0.5–3 MPa, 90-180 min) o'z navbatida 1, 95 va 97, tadqiqot hisoblanishadi raqamlar (RON) bilan, E1, E3 va E9, belgilangan uch kislorod hissa ishlab chiqarilgan bir Pt/Al₂oendo katalizator (99-97; Fourier-Transform infraqizil (FT-IR) spektroskopiya karbonil (1647-1750 sm⁻1) va gidroksil (3566-3736 sm⁻1) spirtlar, ketonlar va efirlarning shakllanishiga mos keladigan yutilish bantlarining ko'rinishini tasdiqladi. E1–e3ni 85, 5 va 10 Vt % da AI-15 avtomobil benziniga aralashtirish oktan sonini 85 dan 96.8 gacha (motor usuli), eng katta daromad (11.8 dona) E15 Vt % bilan olingan 1. Xom ashyo quvvati 730 t/y bo'lgan texnologik oqim sxemasi va moddiy balans ishlab chiqildi va texno-iqtisodiy baholash yillik iqtisodiy foyda 2,744 milliard so'm, mahsulot rentabelligi 7,05% va kapitalni qoplash muddati 23 oyni ko'rsatdi. Natijalar shuni ko'rsatadiki, ilgari yaroqsiz qo'shimcha mahsulot sifatida qaralgan og'ir geksan chiqindilari import o'rnini bosuvchi oktanni kuchaytiruvchi qo'shimchalar uchun hayotiy va iqtisodiy jihatdan jozibador xom ashyo hisoblanadi.

Kalit so'zlar: og'ir geksan chiqindilari; oktanni kuchaytiruvchi qo'shimcha;

katalitik oksidlanish; izomerizatsiya; gaz xromatografiyasi-mass-spektrometriya; FT-IR spektroskopiyasi; benzin aralashtirish; texnik-iqtisodiy baholash.

Аннотация. В цехе по производству полиэтилена совместного предприятия “Uz-Kor Gas Chemical” в качестве технологического остатка образуется отработанная тяжелая гексановая фракция, которая в настоящее время утилизируется без дополнительной ценности и представляет опасность для окружающей среды. В этой работе сообщается о преобразовании этого потока отходов в добавки, повышающие октановое число для автомобильного бензина, путем фракционной перегонки с последующим каталитическим окислением, изомеризацией, алкилированием и этерификацией. Отработанный тяжелый гексан был разделен на три температурные группы (84-180, 180-220 и 220-247 °C) с использованием установки фракционирования ARNS-1E, и каждая группа была охарактеризована методом газовой хромато–масс-спектрометрии (GC-MS, Agilent 5975C/7890A), который выявил состав углеводородных групп, состоящий из 95,63 % парафинов, 0,96 % олефинов, 0,35 % нафтенов и 3,07 % аренов, причем содержание отдельных компонентов варьируется от C_6 до C_{30}. Плотность, показатель преломления, кинематическая вязкость, молекулярная масса и температура застывания монотонно увеличивались с увеличением диапазона кипения фракции (плотность 708,3–740,9 кг/м3; кинематическая вязкость 0,8423–1,6001 мм2/с; молекулярная масса 109,3–139,8 г/моль). Каталитическая очистка трех фракций с $K_2Cr_2O_7$–H_2SO_4 окислительной системе за ст/Al_2O_3 катализаторы (150-200 °c, 0.5–3 МПа, 90-180 мин) производят три кислородсодержащие добавки, которая обозначается как E1, E2 и E3, с исследовательское октановое число (оч) 95, 97 и 99, соответственно; Фурье-ИК - (Фурье-ИК) спектроскопии подтвердили появление карбонильных (1647-1750 $см^{-1}$) и гидроксильных (3566-3736 $см^{-1}$) полосы поглощения в соответствии с образованием спиртов, кетоны и эфиры. При добавлении E1–E3 в автомобильный бензин марки АИ-85 в количестве 5, 10 и 15 мас. % октановое число повышается с 85 до 96,8 (автомобильный метод), при этом наибольший прирост (11,8 единиц) достигается при 15 мас. % E1. Для производства сырья производительностью 730 тонн в год были разработаны технологическая схема и материальный баланс, а технико-экономическая оценка показала, что годовой экономический эффект составляет 2,744 млрд. сум, рентабельность продукции - 7,05 %, а срок окупаемости капитала - 23 месяца. Результаты показывают, что

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отработанный тяжелый гексан, ранее считавшийся непригодным для использования побочным продуктом, является жизнеспособным и экономически привлекательным сырьем для производства импортозамещающих добавок, повышающих октановое число.

Ключевые слова: отработанный тяжелый гексан; добавка, повышающая октановое число; каталитическое окисление; изомеризация; газовая хромато-масс–спектрометрия; инфракрасная спектроскопия; смешивание бензинов; технико-экономическая оценка.

INTRODUCTION.

The accelerating growth of gas-chemical complexes and oil- and gas-processing capacity worldwide is accompanied by a parallel increase in the volume of hydrocarbon-containing residues and by-products that are generated at almost every stage of primary and secondary processing [1–3]. Deep conversion of these residues into competitive, standard-compliant motor and aviation fuels is recognized as one of the most important directions for improving the resource efficiency of the petrochemical sector, while systematic collection and reprocessing of waste streams simultaneously reduces the environmental burden associated with their uncontrolled disposal [4,5]. Among such residues, waste heavy hexane generated in polyethylene- and polypropylene-producing suspension units is of particular interest: it is formed continuously as a mixture of unreacted or thermally degraded hexane carrier and dissolved higher-molecular-weight hydrocarbons, and its accumulation is already estimated at close to two million tonnes annually within the region under study [6].

The chemistry of hydrocarbons and their classification, structure and physicochemical behavior are well established [7,8]; however, the practical value of a waste hydrocarbon stream depends less on generic classification than on a rigorous, feedstock-specific determination of its fractional and group composition, because this composition dictates which conversion route — cracking, isomerization, alkylation, oxidation, or esterification — will be technically and economically justified [9,10]. Octane number is the principal quality parameter governing the resistance of automotive gasoline to knock, and a substantial body of literature has examined routes to raise it, including nuclear-magnetic-resonance-based octane prediction models [11], catalytic isomerization process modification [12], isobutane–olefin alkylation chemistry for high-quality fuel production [13], and reviews of state-of-the-art high-octane gasoline production technologies [14]. In parallel, growing attention has been paid to oxygen-containing (oxygenate)

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additives — alcohols, ethers, esters and ketones — as octane boosters that also improve combustion completeness and reduce carbon monoxide emissions [15,16], although the toxicological profile of some aromatic and oxygenated gasoline components requires that new additive chemistries be evaluated carefully [17]. Renewable and waste-derived feedstocks for such additives are increasingly preferred over petroleum-derived aromatics, both for cost and sustainability reasons [16,18].

Despite this progress, the specific problem of converting the heavy hexane residue of olefin-polymer suspension processes into octane-boosting gasoline additives has not been systematically investigated. Existing octane-improver formulations described in the technical literature are based either on aromatic amines (e.g., N-methylaniline blended with a benzine fraction), on multicomponent mixtures of anilines, methylbutenes and toluene derivatives, or on iron-complex/amide/aromatic-amine packages and dioxolane-methanol derivatives [19,20]; all of these rely on purpose-synthesized or imported reagents rather than on an in-country hydrocarbon waste stream. This creates both an economic burden, because octane-improving imports must be paid for in hard currency, and an environmental liability, because the waste heavy hexane itself accumulates without a defined utilization route.

The present study was carried out on the heavy hexane residue of the primary polyethylene production shop of the “Uz-Kor Gas Chemical” joint venture. The purpose of the work was to develop and scientifically justify a technology for obtaining octane-boosting additives for automotive gasoline from this waste stream and to evaluate the resulting additives’ effect on the octane number of AI-85 automotive gasoline, together with the associated material balance and economic effect of process implementation.

Beyond the immediate technical problem, the present work is aligned with the broader national strategy of the Republic of Uzbekistan for deepening the processing of hydrocarbon raw materials, reducing dependence on imported fuel-quality-improving reagents, and expanding the country’s export potential in high-value petrochemical products [4,5]; it also responds to policy directions on energy conservation and the wider use of alternative and secondary energy resources, as well as to the strategic priority of developing cooperation between industrial enterprises and scientific institutions in the chemical-technology and nanotechnology fields. The specific technological context of the present feedstock deserves emphasis: in the primary polyethylene production shop of “Uz-Kor Gas Chemical,” hexane serves as the suspension (diluent) medium in which ethylene is polymerized; during continuous operation, a portion of the hexane undergoes thermal degradation and becomes progressively enriched with dissolved and

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entrained low-molecular-weight polymer, yielding, over time, a heavy, viscous residue that can no longer be economically recycled back into the suspension loop and must instead be periodically withdrawn from the process as waste. Because this residue combines an already elevated paraffin content with a wide molecular-weight distribution (C_6–C_{30}, as shown below), it is compositionally distinct from ordinary petroleum-refinery slops or used lubricating/motor oils that have previously been investigated for octane-improver or fuel-blending applications [6,10], and its systematic characterization and upgrading therefore constitutes a genuinely new research problem rather than an incremental extension of prior waste-oil valorization studies.

The scientific novelty of the study can be summarized as follows:

- The composition and physicochemical properties of the waste heavy hexane residue of a suspension-process polyethylene shop were determined for the first time using combined GC-MS and standard petroleum-analysis methods (GOST/ASTM).

- The waste heavy hexane was separated into three defined boiling-range fractions (84–180, 180–220, 220–247 °C), and the qualitative and quantitative hydrocarbon composition of each fraction, together with the associated physicochemical properties (density, refractive index, kinematic viscosity, molecular weight, pour point), was established.

- Oxygen-containing isomerized organic compounds were synthesized from the fractionated heavy hexane by oxidation with a $K_2Cr_2O_7$–H_2SO_4 oxidizing mixture in the presence of a Pt/Al_2O_3 catalyst, and the reaction mechanism (radical oxidation, carbocation-mediated isomerization, alkylation and esterification) was established.

- Three octane-boosting additives, E1, E2 and E3, with RON values of 95, 97 and 99, respectively, were obtained, and their physicochemical properties were characterized by FT-IR spectroscopy.

-The influence of E1–E3 on the octane number of AI-85 automotive gasoline was quantified at 5, 10 and 15 wt % blending ratios, and a technological principal flow scheme, material balance, and techno-economic assessment (annual economic effect of 2.744 billion UZS) were developed for practical implementation.0

MATERIALS AND METHODS. 2.1. Feedstock. The object of the study was the waste heavy hexane residue generated in the main polyethylene production shop of the “Uz-Kor Gas Chemical” joint venture, where hexane is continuously used as a suspension medium; the fraction of hexane that undergoes thermal degradation and becomes mixed with residual polymer during the process is periodically removed as a technological waste stream. Samples were collected in

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accordance with ISO 3170 and ASTM D4057 requirements for representative sampling and storage of petroleum products [21].

All chemicals used in the fractionation and catalytic-conversion steps (potassium dichromate, sulfuric acid, platinum-on-alumina catalyst) were of analytical or catalytic grade and were used as received, without further purification. Prior to each experimental campaign, the ARNS-1E fractionating apparatus, the stirred-tank reactor, and the analytical instrumentation (gas chromatograph–mass spectrometer, FT-IR spectrometer, viscometer, pycnometers) were calibrated against certified reference materials, and blank runs were performed to verify the absence of cross-contamination between successive samples.

2.2. Fractional distillation. Preliminary clarification of the waste heavy hexane from mechanical and colloidal impurities was carried out by a sedimentation (settling) technique, after which the clarified product was separated into fractions in an ARNS-1E laboratory petroleum-fractionating unit in accordance with GOST 2177-99. Distillation was carried out stepwise up to 247 °C, yielding three principal cuts: fraction I (84–180 °C), fraction II (180–220 °C) and fraction III (220–247 °C); the combined distillate accounted for up to 99 % of the clarified feed.

2.3. Standard physicochemical analysis.The following standard methods were used to characterize the waste heavy hexane and its fractions: mechanical (insoluble) impurities — GOST 6370-2018; water content — the Dean–Stark method in accordance with GOST 2477-2014; density — the areometric and pycnometric methods in accordance with GOST 3900-85 (ASTM D1298); kinematic viscosity — the Ostwald–Pinkevich capillary viscometer method in accordance with GOST 31391-2009 (ASTM D445); pour point — GOST 20287-2023 (ASTM D97); refractive index was determined by standard refractometry. All measurements were performed in triplicate, with the maximum admissible deviation between replicates not exceeding 0.0004 g for gravimetric determinations.

2.4. Gas chromatography–mass spectrometry (GC-MS). The qualitative and quantitative hydrocarbon composition of the waste heavy hexane and of its individual fractions was determined using an Agilent 5975C inert MSD/7890A GC gas chromatograph–mass spectrometer (Agilent Technologies) equipped with an Agilent HP-INNOWax capillary column (30 m × 250 μm × 0.25 μm). The oven temperature program was 60 °C (10 min hold), heated at 4 °C/min to 220 °C (10 min hold), then at 1 °C/min to 240 °C (20 min hold). The injected sample volume was 0.2 μL (solution in hexane); hydrogen was used as carrier gas at a flow rate of 1 mL/min, and the injector temperature was 250 °C. Electron-impact mass spectra were recorded over the m/z range 10–550, and components were identified using

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the NIST17 spectral library, retaining only assignments with a match quality of 90 % or higher.

2.5. Reactor configuration. The stirred-tank reactor used for catalytic conversion was equipped, in addition to the components listed above, with a gas-inlet valve, an inline filter, a check (non-return) valve, a needle valve, a pressure safety valve (PSV), a product-discharge valve, a K-type thermocouple, a vent valve, and a magnetically coupled stirrer drive; this configuration allowed the reaction atmosphere, pressure and temperature to be controlled independently for each of the three fractions processed, while permitting safe venting of any light gaseous by-products generated during oxidation. The oxidizing reagents (1 M $K_2Cr_2O_7$ and concentrated H_2SO_4) were metered from dedicated feed vessels into the reactor in a 1:4 volume ratio immediately prior to each run, minimizing premature reaction of the oxidant prior to contact with the hydrocarbon substrate.

2.6. Catalytic conversion (oxidation, isomerization, alkylation and esterification). Catalytic conversion of the fractionated heavy hexane was carried out in a 2 L stainless-steel (SS 316L) stirred batch reactor rated to 22 MPa and 300–350 °C, equipped with a magnetically driven stirrer (0–800 rpm), an electric heating jacket (2–3 kW) with PID temperature control, a pressure gauge, a safety relief valve and a K-type thermocouple. The oxidizing mixture consisted of 1 M $K_2Cr_2O_7$ and concentrated H_2SO_4 combined in a 1:4 volume ratio; Pt/Al_2O_3 served as the catalyst for the isomerization and alkylation steps. Reaction conditions were: temperature 150–200 °C (fraction-dependent), pressure 0.5–3 MPa, reaction time 90–180 min, in an acidic medium (pH ≈ 2–3). Fraction I (84–180 °C) was processed under these conditions to yield product E1; fraction II (180–220 °C) was processed at 180–200 °C to yield product E2; and fraction III (220–247 °C) was processed at 200–220 °C to yield product E3.

2.7. FT-IR spectroscopy. The oxygenated reaction products were identified by Fourier-transform infrared spectroscopy on a Shimadzu IRTracer-100 spectrometer over the range 400–4000 cm^{-1} (resolution 4 cm^{-1}; signal-to-noise ratio 60,000:1; scan rate 20 spectra/s), using the KBr pellet technique.

2.8. Octane number determination and gasoline blending. The octane-boosting effect of the fractions and of the synthesized additives E1–E3 was evaluated by blending them into commercial AI-85 automotive gasoline at mass ratios of gasoline:additive equal to 95:5, 90:10 and 85:15. The octane number of the blends was determined by the motor method, consistent with the principles of ASTM D2699 (research method) and ASTM D2700 (motor method).

2.9. Material balance and economic evaluation. A material balance for the proposed process was constructed on the basis of an annual effective operating time of 8000 h and a feedstock (waste heavy hexane) throughput of 730 t/y, using mass-

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conservation relationships for the settling, fractionation, and catalytic-conversion blocks. The techno-economic assessment followed standard capital-cost, operating-cost, profitability and payback-period methodology, with market reference prices for octane-boosting additives, capital equipment and reagents taken at the time of the study.

RESULTS AND DISCUSSION

3.1. Group and fractional composition of the waste heavy hexane. GC-MS analysis of the waste heavy hexane sampled from the polyethylene production shop showed that the residue is a complex hydrocarbon mixture spanning the C_6–C_{30} range, with the principal individual components being hexane, isooctane, decane, dodecane and pentadecane. On a hydrocarbon-class basis (Table 1), the residue consists overwhelmingly of paraffins.

Table 1.

Hydrocarbon group composition of the waste heavy hexane residue (GC-MS)

Hydrocarbon class	Paraffins	Olefins	Naphthenes	Arenes
Content, %	95.625	0.955	0.35	3.07

This overwhelmingly paraffinic composition is consistent with the origin of the waste stream as a hexane carrier solvent contaminated with dissolved oligomeric/polymeric residues rather than with cracked or aromatized material, and it scientifically justifies the choice of oxidative isomerization and alkylation — rather than, for example, aromatization — as the most suitable conversion route for raising the octane number of this feedstock [12,13].

Table 2 summarizes the physicochemical properties of the raw waste heavy hexane and of the three fractions obtained by distillation up to 180, 220 and 247 °C, respectively.

Table 2.

Physicochemical properties of the waste heavy hexane and its fractions

Sample	Density at 20 °C, kg/m³ (GOST 3900-2002)	Refractive index	Kinematic viscosity at 20 °C, mm²/s (GOST 31391-2020)	Molecular weight, g/mol	Pour point, °C (GOST 20287-2023)
Raw waste	708.3	1.402	0.8423	109.3	−53

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Sample	Density at 20 °C, kg/m³ (GOST 3900-2002)	Refractive index	Kinematic viscosity at 20 °C, mm²/s (GOST 31391-2020)	Molecular weight, g/mol	Pour point, °C (GOST 20287-2023)
heavy hexane					
Fraction I (84–180 °C)	726.2	1.412	1.3259	139.9	−44
Fraction II (180–220 °C)	737.9	1.418	1.6008	139.8	−32
Fraction III (220–247 °C)	740.9	1.419	1.6001	139.8	−30

The systematic increase in density, refractive index, kinematic viscosity and molecular weight, together with the increase in pour point, from the raw residue to the heaviest fraction confirms the progressive concentration of longer-chain hydrocarbons during fractionation and demonstrates that the distillation step successfully separated the feedstock into fractions with distinguishable and reproducible physicochemical profiles, a prerequisite for a controlled downstream catalytic conversion [9].

3.2. GC-MS compositional profile of the individual fractions. The light fraction (up to 180 °C) was dominated by C_6–C_{12} paraffins (Table 3): hexane (14.51 %), isooctane (19.00 %), 3-methylheptane (9.12 %), n-decane (21.90 %) and dodecane (14.66 %) together accounted for close to 80 % of this cut.

Table 3.

Hydrocarbon composition of the fraction distilled up to 180 °C

Component	Retention time, min	Content, %
Hexane	0.930	14.51
Methylcyclopentane	0.952	4.97
Hexahydrobenzene	0.962	2.31
3-Methylheptane	0.997	9.12
Isooctane	1.014	19.00
1-Cyclopentylpropane	1.098	0.69
5-Methylnonane	1.255	5.00

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Component	Retention time, min	Content, %
3-Methylnonane	1.289	2.11
n-Decane	1.401	21.90
1-Hexyl-2-methylcyclopropane	1.525	0.51
Methylundecane	2.367	0.71
3-Methylundecane	2.553	0.33
Dodecane	3.002	14.66
n-Tetradecane	8.859	0.62

The intermediate fraction (180–220 °C) was dominated by dodecane (43.70 %) and pentadecane (17.05 %), together with decane (18.59 %) (Table 4), while the heaviest fraction (220–247 °C) was dominated by pentadecane (36.41 %), dodecane (35.22 %) and eicosane (12.25 %), with smaller contributions from nonacosane and higher homologues up to dotriacontane (Table 5).

Table 4.

Hydrocarbon composition of the fraction distilled between 180 and 220 °C

Component	Retention time, min	Content, %
Octane	1.025	3.73
Nonane	1.205	0.11
3-Methylnonane	1.300	1.99
Decane	1.401	18.59
5-Methylundecane	2.390	2.99
Undecane	2.575	1.46
Dodecane	3.215	43.70
Tridecane	7.354	0.32
Pentadecane	9.094	17.05
Eicosane	21.987	2.56

Table 5.

Hydrocarbon composition of the fraction distilled between 220 and 247 °C

Component	Retention time, min	Content, %
Decane	1.96	4.83
Undecane	2.379–2.581	3.03
Dodecane	2.232	35.22
Tridecane	6.714–7.376	2.60
Pentadecane	9.510	36.41
Eicosane	22.588	12.25
Nonacosane	39.698	2.10
10-Methylnonadecane	43.269	0.50
Dotriacontane	44.314	0.08

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The progressive shift of the dominant carbon number from C_6–C_{10} in the light cut to C_{15}–C_{20} in the heavy cut confirms an effective and controllable fractionation and provides the compositional basis required to select the oxidative conversion conditions applied to each cut individually.

3.3. Catalytic oxidation, isomerization, alkylation and esterification chemistry. Long, straight-chain saturated hydrocarbons such as those dominating the waste heavy hexane fractions are characterized by a low research octane number (RON 20–30) because of their propensity to auto-ignite (detonate) under compression [12]. Two complementary strategies were used to raise the octane rating of these paraffins: (i) partial oxidation to oxygen-containing organic compounds (alcohols, ketones, ethers, esters), and (ii) skeletal isomerization to branched isoalkanes, optionally combined with alkylation and esterification.

In the oxidative pathway, the $K_2Cr_2O_7$–H_2SO_4 system generates atomic oxygen and, indirectly, hydroxyl and alkoxy radicals:

$$2K_2Cr_2O_7 + 8H_2SO_4 \rightarrow 2K_2SO_4 + 2Cr_2(SO_4)_3 + 8H_2O + [O]$$

$$R–H + [O] \rightarrow R\bullet + \bullet OH$$

$$R\bullet + \bullet OH \rightarrow RO\bullet + ROH \rightleftharpoons RO\bullet + \bullet OH \rightarrow ROH + O\bullet$$

which, for example, converts n-decane into decanol and decanone isomers; in the presence of the Pt/Al_2O_3 catalyst, chain restructuring proceeds further toward hydroxylated and carbonylated branched species:

$$R–CH_2–CH_3 \rightarrow R–CH=CH_2 + \bullet OH \rightarrow R–CH(OH)–CH_2OH + R–CO–CH_3$$

Table 6 lists the classes of oxygen-containing products obtained and their approximate contribution to octane rating.

Table 6.

Principal products formed during catalytic oxidation of the paraffinic fractions

Product class	General formula	RON (indicative)	Characteristic
Monohydric alcohol	$CH_3(CH_2)_nCHOHCH_3$	95	Good oxygen donor, clean combustion
Monohydric alcohol (isomer)	$CH_3(CH_2)_nCHOHCH_3$	96	Improves combustion stability
Ketone	$CH_3(CH_2)_nCOCH_3$	100	Stable, high octane
Ether	$CH_3(CH_2)_nO(CH_2)_nCH_3$	105	Introduces oxygen, lowers CO_2

In parallel, acid-catalyzed skeletal isomerization of the n-alkanes proceeds through protonation, carbocation formation, hydride/methyl shift, and

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deprotonation:

$CH_3–(CH_2)_n–CH_3 + H^+ \rightarrow CH_3–(CH_2)_n–CH^+–CH_3 \rightarrow$ (1,2-hydride/methyl shift) → branched carbocation → isoalkane + H^+

Table 9 (Section 3.9, in the original process design) lists Pt/Al_2O_3, $Pt–SO_4^{2-}$, Pt/H-Y zeolite and $WO_3–ZrO_2$ as candidate isomerization catalysts, of which Pt/Al_2O_3 was selected for the present work owing to its high activity and selectivity under the mild oxidative-acidic conditions used. Isomerization of n-decane under these conditions (150–200 °C, 1–3 MPa, 90–120 min, $K_2Cr_2O_7/H_2SO_4$ as a mild acid-oxidant medium) achieved a conversion of 70–90 %, yielding branched C_8–C_9 isomers such as 2,2,5-trimethylhexane and 2,2,4-trimethylpentane with RON values of 97–100 (Table 7).

Table 7.

Isomerization products of n-decane and their octane numbers

Product	Formula	RON	Remark
2,2,5-Trimethylhexane	C_9H_{20}	97–100	Isooctane analogue, high octane
2,5-Dimethylheptane	C_9H_{20}	94	Stable combustion, low smoke
3,4-Dimethylhexane	C_8H_{18}	92	High thermal stability
2,2,4-Trimethylpentane	C_8H_{18}	100	Reference isooctane

Alkylation of the paraffinic fractions with light olefins over Pt/Al_2O_3 (and, in supplementary trials, $MnO_2–SO_4^{2-}$) produced isoparaffins with RON 95–100, while acid-catalyzed esterification of the intermediate alcohols (e.g., decanol, dodecanol) with organic acids yielded oxygenated esters (decyl acetate, dodecyl formate) with RON 95–105, and transesterification over Pt/Al_2O_3 produced methyl/ethyl decanoates and dodecanoates with RON 90–100 (Table 8).

Table 8.

Comparison of catalytic conversion routes

Reaction type	Catalyst	Main product	Effect on octane number	Practical significance
Alkylation	Pt/Al_2O_3	Isodecane, isododecane	Strong increase (95–100)	Gasoline blend components
Esterification	H_2SO_4, Pt/Al_2O_3	Esters (decyl acetate)	Strong increase (95–105)	Octane-boosting ethers/esters

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Reaction type	Catalyst	Main product	Effect on octane number	Practical significance
Transesterification	Pt/Al_2O_3	Methyl/ethyl decanoates	Strong increase (90–100)	Biofuel-type components

Taken together, these reaction pathways raise the octane number of the paraffinic feedstock from an initial RON of 20–35 to 95–105 in the model reaction products, while improving combustion completeness and reducing exhaust-gas volume — findings that are consistent with, and extend to a waste-derived feedstock, the broader literature on oxygenate- and isoparaffin-based octane improvers [11,13,15].

3.4. GC-MS analysis of the oxidized reaction products. GC-MS analysis of the catalytically treated 180 °C fraction (Table 9) confirmed the appearance of diethyl ether (1.37 %), isopropanol (0.72 %), and butanol (0.74 %) alongside retained isooctane (14.36 %), decane (10.39 %), and dodecane (13.24 %); the calculated weighted-average RON of this blend was approximately 92, reflecting the combined contribution of branched hydrocarbons and oxygenates.

Table 9.

Compositional changes after catalytic treatment of the fraction distilled up to 180 °C

Component	Retention time, min	Content, %	Match quality, %
Diethyl ether	2.776	1.37	88
Isopropanol	4.483	0.72	2
Octane	4.879	8.16	87
Isooctane	4.958	14.36	74
Heptyl-hexyl ether	7.476	4.91	78
Decane	8.146	10.39	93
Undecane	10.548	7.61	74
Dodecane	11.200	13.24	87
Butanol	13.321	0.74	86
Heptadecane	14.083	20.02	80

Analysis of the fraction treated above 180 °C (Table 10) revealed a markedly higher proportion of branched hydrocarbons and cyclic ethers, including 2-ethyl-2-methyloxirane (18.25 %), 3-methylheptane (21.51 %), and isodecane (11.37 %), together with methanol (3.69 %), consistent with more extensive isomerization and oxygenation at the harsher processing conditions applied to the heavier cut.

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Table 10.

Compositional changes after catalytic treatment of the fraction distilled above 180 °C

Component	Retention time, min	Content, %	Match quality, %
Methanol	2.569	3.69	37
2-Methylbutane	2.636	6.66	47
2-Ethyl-2-methyloxirane	2.758	18.25	47
3-Methylpentane	2.928	6.16	60
3-Methylheptane	4.452	21.51	80
2,3-Dimethylheptane	4.848	12.05	59
3-Ethyl-2-methylhexane	7.451	3.14	86
Isodecane	8.134	11.37	90
Dodecane	11.194	17.17	87

For the fraction treated above 220 °C, isooctane (11.35 %), 2,3-dimethyldecane (25.32 %), propyl-dodecyl ether (20.09 %), isotetradecane (23.36 %) and isononadecane (8.90 %) were identified, indicating that both branching and etherification proceed extensively at the higher processing temperature, in agreement with the RON = 99 obtained for the corresponding additive E3.

3.5. FT-IR characterization of the octane-boosting additives. FT-IR spectra of the three chemically treated fractions confirmed the formation of oxygen-containing functional groups predicted by the proposed reaction mechanism. In the additive obtained from the 180 °C fraction, strong absorptions at 2957.60, 2923.20 and 2855.81 cm^{-1} were assigned to C–H stretching of $–CH_2–$ and $–CH_3$ groups, confirming the long-chain aliphatic backbone; bands at 1458.01 and 1377.73 cm^{-1} corresponded to $–CH_2–$ deformation and symmetric $–CH_3$ deformation, respectively, while bands at 722.56 and 668.08 cm^{-1} were assigned to long-chain $–(CH_2)_n–$ rocking vibrations. Critically, bands at 1750.48 and 1647.25 cm^{-1} were attributed to carbonyl (C=O) stretching, consistent with the formation of esters, aldehydes and conjugated carbonyl species.

In the additive obtained from the fraction treated above 180 °C, broad absorptions at 3736.07, 3650.05 and 3566.90 cm^{-1} were assigned to free O–H stretching of alcohols and carboxylic acids, while the band at 1744.74 cm^{-1} confirmed strong carbonyl character (esters, higher fatty-acid oxides) and the band at 1684.53 cm^{-1} was attributed to ketone and conjugated C=C/N–H absorption. A weaker band at 1508.19 cm^{-1} indicated the presence of aromatic C=C bonds, and the 721.12 cm^{-1} band confirmed long-chain branched hydrocarbons. The spectrum of the additive obtained from the fraction treated above 220 °C reproduced the same O–H (3566–3736 cm^{-1}) and C=O (1647.25, 1750 cm^{-1}) features, together with an

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additional band at 2348.3 cm^{-1} attributable to atmospheric O=C=O and bands at 1541.17 and 1508.19 cm^{-1} confirming N–H and aromatic C=C absorptions, respectively.

Collectively, the systematic appearance of O–H and C=O absorption bands across all three treated fractions provides direct spectroscopic confirmation that the $K_2Cr_2O_7$–H_2SO_4/Pt–Al_2O_3 system converts the paraffinic waste hexane fractions into the oxygenated, isomerized products (alcohols, ketones, ethers, esters) responsible for the observed octane improvement, corroborating the GC-MS results in Section 3.4.

3.6. Effect of the additives on the octane number of AI-85 gasoline. Blending trials were first performed with the untreated (raw) fractions to establish a baseline. As shown in Table 11, the octane number of the resulting blends increased with both the boiling range of the fraction used and the blending ratio, rising from 30 (raw feed alone) to 74 for fraction III at an 85:15 (gasoline:fraction) ratio; this baseline confirms that even without catalytic modification, the heavier, more paraffin-concentrated fractions provide some octane benefit, consistent with their higher content of branched and cyclic species (Section 3.2).

Table 11.

Effect of the raw fractions on the octane number of AI-85 gasoline blends

Fraction	Boiling range, °C	Baseline RON	Blend ratio (gasoline:additive)	Blend RON
Raw waste heavy hexane	—	30	95:5	34
			90:10	39
			85:15	41
Fraction I	84.1–180	61	95:5	64
			90:10	69
			85:15	72
Fraction II	180–220	64	95:5	64
			90:10	69
			85:15	72
Fraction III	220–247	76	95:5	72
			90:10	73
			85:15	74

After catalytic treatment, the resulting additives E1 (from fraction I, RON 95), E2 (from fraction II, RON 97) and E3 (from fraction III, RON 99) produced substantially larger octane gains (Table 12). E1 raised the octane number of AI-85 gasoline from 85 to 88.9, 93.2 and 96.8 at blending ratios of 5, 10 and 15 wt %, respectively — a maximum gain of 11.8 units. E2 produced gains of 1.8–7.6 units

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(final RON 86.8–92.6), and E3 produced gains of 2.4–9.1 units (final RON 87.4–94.1). A combined blend of E1, E2 and E3 in equal proportion produced intermediate gains of 2.7–9.5 units.

Table 12.

Effect of the catalytically treated additives (E1–E3) on the octane number of AI-85 gasoline

Additive	Treatment temperature, °C	Blend ratio (gasoline:additive)	Blend RON
E1	150–180	95:5	88.9
		90:10	93.2
		85:15	96.8
E2	180–200	95:5	86.8
		90:10	89.1
		85:15	92.6
E3	200–220	95:5	87.4
		90:10	91.7
		85:15	94.1
E1+E2+E3 (combined)	150–180	95:5	87.7
		90:10	91.5
		85:15	94.5

The superior performance of E1 relative to E2 and E3 is attributed to the milder oxidation temperature applied to the lightest fraction, which favored the formation of low-molecular-weight, highly branched and oxygenated species (Section 3.4, Table 9) with the strongest inherent octane-boosting effect, whereas the heavier fractions, despite a higher content of branched paraffins, retained a larger proportion of straight-chain, higher-boiling material that partially offset the benefit of oxygenation. Overall, the results confirm that a 15 wt % addition of E1 to AI-85 gasoline meets and exceeds the octane requirement of AI-92/AI-95-grade gasoline, demonstrating the technical feasibility of the proposed valorization route.

3.7. Proposed technological scheme and material balance. A principal technological flow scheme was developed for continuous conversion of the waste heavy hexane into octane-boosting additives. Waste heavy hexane is first pumped into a settling vessel, where mechanical particles and heavy impurities are separated by gravity; the clarified hexane is then pumped through a heat exchanger and a fired heater (up to 300 °C) into a fractionating column. Light volatile fractions leave the top of the column, are condensed in air and water coolers, and are separated in a knock-out drum, with a portion returned to the column as reflux. Within the column, three principal fractions are withdrawn according to their

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boiling range and, after cooling, are each pumped to a dedicated stirred-tank reactor, where they are treated with the 1 M $K_2Cr_2O_7$/concentrated H_2SO_4 oxidizing mixture (prepared in dedicated reagent vessels) at 150–220 °C and approximately 0.3 MPa, using steam heating, to yield additives E1, E2 and E3, respectively. The column bottoms (heavy residue) are withdrawn separately.

The material balance was calculated for a feedstock throughput of G_1 = 730 t/y (G_1' = 91.25 kg/h) at an annual effective operating time of 8000 h, together with $K_2Cr_2O_7$ consumption of G_2 = 0.2521 t/y and H_2SO_4 consumption of G_3 = 5.0575 t/y. Low-molecular-weight polymer impurities separated during clarification amounted to G_4 = 131.4 t/y (18 % of feed); the clarified hexane (598.6 t/y) was distributed among fraction I (299.90 t/y, x_3 = 0.501), fraction II (155.64 t/y, x_4 = 0.26), fraction III (75.42 t/y, x_5 = 0.126) and a residual bottoms stream (65.85 t/y, x_6 = 0.11), with a light-gas fraction of 1.80 t/y (x_7 = 0.003). Accounting for a 1 wt % addition of the oxidizing mixture to each distillate stream (x_8 = 0.01), the resulting annual yields of the additives were G_6 (E1) = 302.90 t/y, G_7 (E2) = 157.19 t/y and G_8 (E3) = 76.18 t/y — a combined annual additive output of 536.27 t/y from 730 t/y of feedstock, i.e., a 73.5 % overall mass yield (Table 13). An auxiliary catalyst consumption of 5 t/y of Al_2O_3–Pt was also established.

Table 13.

Material balance of the waste heavy hexane conversion process (feed capacity 730 t/y)

Stream	t/y	kg/h	mass %
Input			
Waste heavy hexane	730.000	91.250	99.278
$K_2Cr_2O_7$	0.252	0.0315	0.034
H_2SO_4	5.057	0.632	0.688
Total input	**735.310**	**91.914**	**100**
Output			
Low-molecular polymer impurities	131.400	16.425	17.870
Off-gas	1.796	0.0224	0.244
Additive E1	302.898	37.862	41.193
Additive E2	157.192	19.645	21.377
Additive E3	76.178	9.522	10.360
Residual bottoms	65.846	8.231	8.956
Total output	**735.310**	**91.707**	**100**

3.8. Techno-economic assessment. The techno-economic assessment was performed for the Bukhara oil refinery (“Buxoro neftni qayta ishlash zavodi” LLC, part of the “Uzbekneftegaz” joint-stock company) as the illustrative

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implementation site. At a prevailing market price of 11.64, 11.76 and 11.52 million UZS per tonne for E1, E2 and E3, respectively, the annual revenue from additive sales was calculated as A_1 = 3.526 billion UZS (E1), A_2 = 1.849 billion UZS (E2) and A_3 = 0.878 billion UZS (E3), giving a total annual revenue of A_{total} = 6.252 billion UZS.

Capital expenditure for implementing the new technology comprised design, commissioning and pilot-sample costs of 0.8 billion UZS and equipment/installation costs of 4.447 billion UZS (four reactors, a settling vessel, a fractionating column, storage vessels, seven pumps, heat exchangers, air and water coolers, a fired heater, a separator, piping and instrumentation, transportation and installation), giving a total capital investment of T_{impl} = 5.247 billion UZS (Table 14).

Table 14.

Capital expenditure for implementation of the proposed technology

Cost item	Amount, million UZS
Process design	600
Commissioning	100
Pilot-sample production	100
Sub-total (implementation)	**800**
Reactors (4 units)	1600
Settling vessel	100
Fractionating column	1200
Storage/reagent vessels (3)	60
Pumps (7)	280
Heat exchanger	80
Air coolers (4)	80
Water coolers (4)	100
Fired heater	300
Separator	100
Instrumentation and piping accessories	17
Auxiliary materials	300
Transportation	80
Installation and commissioning of equipment	90
Miscellaneous	60
Sub-total (equipment)	**4447**
Total capital investment (T_{impl})	**5247**

Annual production and operating costs, dominated by raw-material (waste heavy hexane, 1825.0 million UZS) and catalyst (Al_2O_3–Pt, 991.7 million UZS)

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costs, net of the value of recoverable by-products (low-molecular polymer and residual heavy fraction), totaled 3457.8 million UZS in direct production costs; including administrative and sales overheads of 50.0 million UZS, the full cost of production reached 3507.8 million UZS/y (Table 15).

Table 15.

Annual production and operating costs

Cost item	Annual consumption	Unit price, UZS	Annual cost, thousand UZS
Waste heavy hexane feedstock	730,000 kg	2,500	1,825,000.0
Recovered polymer (by-product credit)	131,400 kg	3,000	394,200.0
Recovered heavy fraction (by-product credit)	65,846 kg	2,000	131,692.0
Process steam	16,000 kg	1,000	16,000.0
Al_2O_3–Pt catalyst	1,666.7 kg	595,000	991,662.7
$K_2Cr_2O_7$	252.1 kg	1,000	252.1
H_2SO_4	5,057.5 kg	1,500	7,586.2
Electric power	40,000 kWh	2,000	80,000.0
Total material costs (net of by-product credit)			**2,931,911.0**
Labor costs (2 employees)			8,000.0
Social-security contributions			2,550.0
Depreciation of fixed assets			250.0
Other costs			30.0
Total production cost			**3,457,803.0**
Administrative and sales overheads			50,000.0
Full cost of production			**3,507,803.0**

The resulting annual profit was F = A − (production and operating costs) = 6.252 − 3.508 = 2.744 billion UZS. Product profitability, defined as F divided by production and operating costs, was 2.744/35.078 × 100 % = 7.05 %, and the capital payback period, $\tau = T_{impl}/F = 5.247/2.744 = 1.92$ years (approximately 23 months). These figures indicate that, at the prevailing octane-additive market price, conversion of waste heavy hexane into E1–E3 additives is both technically feasible and economically self-sustaining within a two-year investment horizon, in addition to eliminating an environmentally problematic waste stream.

3.9. Consolidated FT-IR band assignment. For clarity, Table 16 consolidates

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the diagnostic FT-IR absorption bands observed across the three catalytically treated fractions and their structural assignments, providing a single reference point for the spectroscopic evidence discussed in Section 3.5.

Table 16.

Consolidated FT-IR band assignments for additives E1–E3

Wavenumber range, cm^{-1}	Assignment	Structural implication
3736–3566	O–H stretching (free)	Alcohols, carboxylic acids
2957–2854	C–H stretching (–CH_2–, –CH_3)	Long-chain aliphatic backbone
2348	O=C=O stretching	Atmospheric CO_2 (background)
1750–1647	C=O stretching	Esters, aldehydes, ketones, conjugated carbonyls
1684	C=O / C=C / N–H	Ketones, conjugated unsaturation
1559–1541	N–H bending (amide II region)	Trace nitrogen-containing species
1508	Aromatic C=C	Residual aromatic/arene content
1458–1375	CH_2/CH_3 deformation	Branched aliphatic structure
722–668	–$(CH_2)_n$– rocking	Long, unbranched alkyl segments

The internal consistency of these assignments across all three additives — persistent long-chain C–H stretching combined with a systematic and reproducible appearance of O–H and C=O bands only after catalytic treatment — provides strong, independent structural confirmation of the oxidation/isomerization mechanism proposed in Section 3.3 and of the GC-MS identification of alcohols, ethers, and esters reported in Section 3.4.

3.10. Comparison with the literature and industrial relevance. The octane-boosting performance achieved in this work (RON up to 99 for the neat additive E3 and a blended AI-85 octane number of up to 96.8) is comparable to, and in several respects exceeds, values reported for oxygenate- and isoparaffin-based octane improvers derived from conventional or renewable feedstocks [11,13,15,16], while relying on a feedstock that is presently a net environmental liability rather than a purchased raw material. Unlike aromatic-amine-based commercial octane improvers, whose long-term combustion toxicology has been questioned [17], the additives obtained in this study are structurally dominated by aliphatic alcohols, ketones and ethers, which are generally associated with a more favorable emissions and toxicological profile, consistent with the broader shift toward oxygenate-based, non-aromatic octane enhancement strategies documented

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in the recent literature [14,15]. From an industrial-implementation perspective, the fact that the proposed process uses commercially available, low-cost oxidant and catalyst systems ($K_2Cr_2O_7/H_2SO_4$, Pt/Al_2O_3) rather than specialized proprietary reagents, and that it can be integrated directly at the site where the waste stream is generated, materially reduces both the capital intensity and the logistical complexity of implementation relative to import-substitution strategies based on synthetic octane-improver packages.

At the same time, several limitations of the present study should be acknowledged. First, the reported octane numbers were obtained on a laboratory scale using batch reactors and motor-method octane determination; validation on a continuous pilot unit, and confirmation by the standard research-method (RON) and motor-method (MON) engine tests specified in ASTM D2699/D2700, will be required before large-scale deployment. Second, the long-term storage stability of the oxygenated additives, their compatibility with existing fuel-distribution and engine-sealing materials, and their behavior in phase-separation and water-tolerance tests were outside the scope of the present investigation and merit dedicated follow-up studies, in line with established practice for the qualification of new fuel oxygenates [14,16]. Third, the economic analysis presented in Section 3.8 is based on prevailing reagent, equipment and product-market prices at the time of the study and on a single implementation site; sensitivity of the payback period to feedstock availability, reagent-price volatility and octane-additive market price would benefit from further scenario analysis before investment decisions are finalized.

CONCLUSION. Waste heavy hexane generated in the polyethylene production shop of the “Uz-Kor Gas Chemical” joint venture, previously accumulated without a defined utilization pathway, was shown to be a technically and economically viable feedstock for octane-boosting automotive gasoline additives. Fractional distillation separated the waste stream into three cuts (84–180, 180–220, 220–247 °C) with progressively increasing density, viscosity, molecular weight and pour point, and GC-MS analysis established an overwhelmingly paraffinic bulk composition (95.6 %) spanning the C_6–C_{30} range. Catalytic oxidation of these fractions with a $K_2Cr_2O_7$–H_2SO_4 oxidizing mixture over a Pt/Al_2O_3 catalyst, proceeding through radical oxidation, carbocation-mediated isomerization, alkylation and esterification, produced three octane-boosting additives, E1, E2 and E3, with RON values of 95, 97 and 99, whose oxygenated (alcohol, ketone, ether) character was independently confirmed by FT-IR spectroscopy. Blending these additives into AI-85 automotive gasoline at 5–15 wt % raised the octane number by 2.4–11.8 units, with the best performance (RON 96.8) obtained using 15 wt % of additive E1. A process flow scheme and material

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balance were developed for a feedstock capacity of 730 t/y, converting it into 536.3 t/y of combined additive output (73.5 % mass yield), and a techno-economic assessment demonstrated an annual economic benefit of 2.744 billion UZS, a product profitability of 7.05 %, and a capital payback period of approximately 23 months. These results support the practical implementation of the proposed technology at petroleum-refining and petrochemical enterprises within the Republic of Uzbekistan, both as a means of import substitution for octane-boosting additives and as an environmentally beneficial route for the utilization of an otherwise unmanaged industrial waste stream. Future work should extend the present laboratory-scale findings to pilot-scale continuous operation, evaluate the storage stability and corrosion/compatibility behavior of the additives in commercial fuel-distribution infrastructure, and quantify the emissions benefit of the additives in engine-bench tests.

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