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Economic Viability of Producing Unsaturated Polyester from Recycled PET Waste

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الجدوى الاقتصادية لإنتاج البوليستر غير المشبع من نفايات البولي إيثيلين تيريفثالات المعاد تدويرها

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Abstract:
The abstract discusses the synthesis of unsaturated polyester resins (UPe) derived from maleic anhydride and glycolysis products of polyethylene terephthalate (PET), with dipropylene glycol (DPG) acting as the medium in the presence of tetrabutyl titanate catalyst. The characterization of both the glycolyzed waste PET and the UPes utilized FTIR and NMR spectroscopy, along with elemental analysis, acid value (AV), hydroxyl value (HV), and iodine value assessments. Additionally, nanocomposites were developed using UPe and hexamethyldisilazane modified silica nanoparticles, highlighting a significant applicative potential for UPe resins. A techno-economic analysis was performed to evaluate the viability of this innovative UPe production technology, which leverages recycled waste PET as a raw material. This not only helps conserve natural resources but also provides economic benefits by reducing costs. The study emphasizes that adopting this approach aligns with principles of the green economy, prioritizing environmental protection and profitability without contributing to pollution. The integration of these principles underscores the development of sustainable practices in UPe production, thereby offering an eco-friendly solution.

Keywords: Unsaturated polyester, Modified silica, Nanocomposite, Profitability, Green economy.

الملخص:
يتناول هذا الملخص عملية تصنيع راتنجات البوليستر غير المشبع (UPe) المشتقة من أنهيدريد الماليك ونواتج التحلل الجليكولي لبولي إيثيلين تيريفثاليت (PET)، باستخدام ثنائي بروبيلين جليكول (DPG) كوسط تفاعل، وبوجود تيتانات رباعي البوتيل كحفاز. وقد تم توصيف كل من نواتج التحلل الجليكولي لنفايات الـ PET وراتنجات الـ UPe الناتجة باستخدام تقنيات مطيافية الأشعة تحت الحمراء (FTIR) والرنين المغناطيسي النووي (NMR)، بالإضافة إلى إجراء التحليل العنصري، وتحديد الرقم الحمضي (AV)، والرقم الهيدروكسيلي (HV)، والرقم اليودي. علاوة على ذلك، تم تطوير مواد نانوية مركبة (nanocomposites) باستخدام راتنجات الـ UPe وجسيمات السيليكا النانوية المُعدلة بمركب سداسي ميثيل ثنائي سيلازان (hexamethyldisilazane)، مما يبرز إمكانات تطبيقية واعدة لراتنجات الـ UPe. كما أُجري تحليل تقني-اقتصادي لتقييم جدوى تقنية إنتاج الـ UPe المبتكرة هذه، والتي تعتمد على إعادة تدوير نفايات الـ PET كمادة خام. ولا يقتصر أثر ذلك على الحفاظ على الموارد الطبيعية فحسب، بل يحقق أيضاً فوائد اقتصادية من خلال خفض التكاليف. وتؤكد الدراسة أن تبني هذا النهج يتماشى مع مبادئ الاقتصاد الأخضر، حيث يمنح الأولوية لحماية البيئة وتحقيق الربحية دون التسبب في التلوث. ويؤكد دمج هذه المبادئ على تطوير ممارسات مستدامة في إنتاج الـ UPe، مما يوفر حلاً صديقاً للبيئة.

الكلمات المفتاحية: البوليستر غير المشبع، السيليكا المُعدلة، المواد النانوية المركبة، الربحية، الاقتصاد الأخضر.

1– Introductionion

Poly(ethylene terephthalate) (PET) is a semi-crystalline thermoplastic polyester known for its excellent mechanical properties and high transparency. The consumption of PET packaging has surged significantly,

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contributing to an increase in non-renewable waste in landfills. [1]According to a recent packaging market analysis, global PET packaging consumption is projected to exceed 20 million tons by 2019, equating to a growth rate of 4.6% during the period from 2014 to 2019. This rise in consumption leads to essential ecological concerns, notably heightened greenhouse gas emissions and underutilization of potential energy, thereby escalating the necessity for plastic recycling. Waste PET can undergo recycling through several alternative methods, including re-extrusion (primary), mechanical (secondary), chemical (tertiary), and energy recovery (quaternary) processes. [2,3]

Chemical recycling of polymers, particularly PET, is recognized for its potential in reducing pollution and offering a cost-effective alternative to traditional plastic disposal. The depolymerization of PET through various chemical processes—including hydrolysis, alcoholysis, glycolysis, and aminolysis—facilitates the breakdown of macromolecular chains into lower molecular weight products. This versatility in chemical recycling supports the production of oligomeric and monomeric entities with distinct functionalities, depending on the choice of reagents used. [4]

Unsaturated polyesters (UPes) represent a critical class of thermosetting resins employed in the manufacture of reinforced plastics, electrical components, and other industrial applications, showcasing significant economic promise. [5,6] The incorporation of modified silica nanoparticles into polymer matrices has been shown to enhance the mechanical and thermal properties of nanocomposite materials significantly. These modifications improve the dispersion, stability, and compatibility of the nanofillers within the polymer, leading to superior dynamic-mechanical properties even at low concentrations.

Optimizing the production process of UPes using recyclable materials, particularly[7,8] those derived from the depolymerization of waste PET through trans-esterification with various reactants, has been identified as a method to enhance market competitiveness against commercially sourced alternatives. [9] A techno-economic evaluation indicates that the substitution of conventional raw materials with products derived from recycled PET could yield positive indicators for production viability. [10,11]

Despite the various technologies developed for UPe production, the ongoing need for refinement and innovation is evident. This conclusion arises from a comprehensive survey of current technologies, aiming to elevate capabilities in line with regulatory requirements and practical implementation. Precise cost analyses focusing on raw materials and operational expenses are essential to assess the feasibility of scaling these technologies from pilot projects to full-scale applications. [12,13,14,15]

The present study investigates the optimal synthesis of UPes using waste PET glycolysis products and silica nanocomposite materials. Di-hydroxy functional products generated through catalytic glycolysis of PET waste using dipropylene glycol and maleic anhydride serve as the basis for UPe synthesis. A preliminary techno-economic analysis was conducted to evaluate the commercial viability, emphasizing cost elements related to raw materials and operations. Hybrid composite materials combining UPes with chemically modified silica nanoparticles were also prepared, highlighting both the applicability and market value of UPe and its associated products. [16,17,18]

2 -Experimental part

The experimental part of the study focused on the development of technology for the production of unsaturated polyesters (UPes) and nanocomposites using UPes and hexamethyldisilazane-modified silica as a reinforcing agent. The entire process consisted of four main steps: (a) production and purification of glycolysis products derived from waste PET and dipropylene glycol (DPG); (b) synthesis of unsaturated polyesters from waste PET glycolizates; (c) generation of nanocomposite materials from UPes and modified silica nanoparticles; and (d) a techno-economic analysis of UPe production.

In the materials section, PET waste sourced from soft drink bottles was processed into small flakes (approximately 0.5 × 0.5 cm). To eliminate any impurities and residual adhesives, the flakes were treated with a detergent, ethanol, and dichloromethane. DPG, a mixture comprising 4-oxa-2,6-heptandiol, 2-(2-hydroxypropoxy)-propan-1-ol, and 2-(2-hydroxy-1-methylethoxy)-propan-1-ol, along with other chemicals such as styrene, tetrabutyl titanate (TBT), xylene, and dichloromethane, were acquired from Fluka. Other compounds, including toluene, pyridine, tetrahydrofuran (THF), 2-butanone peroxide, cobalt octoate, m-xylene, maleic anhydride, and hydroquinone, were sourced from Sigma-Aldrich. All chemicals were utilized as received without further purification. Aerosil R812S, hydrophobic fumed silica treated with HMDS and characterized by a surface area of 220±25 m^2/g, was provided by Evonik.

The production of the PET glycolizate involved depolymerization of the PET waste using glycolysis with DPG in a four-necked round-bottom reactor utilizing both classical and ethylene glycol (EG) azeotropic removal methods. For the classical method, a specific reaction mixture comprised 92.0 g of purified, dried, and chopped PET (0.474 mol), 92.0 g of DPG (0.686 mol), and 0.28 ml of TBT catalyst, was heated to 210-220°C for 6 hours under inert conditions with mechanical stirring. Following glycolysis, the reaction mixture was dissolved in dichloromethane (200 ml) and washed with distilled water to remove excess alcohols. Finally, the product was

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filtered, dried in an oven at 90°C for 24 hours, and subsequently dried in a vacuum oven at 80°C for 3 hours, leading to the final product designated as DPG.
The ethylene glycol (EG) azeotropic removal method was executed similarly to method 2.2 a), with a key alteration in the procedure. After a three-hour glycolysis process, a Dean-Stark water separator was incorporated to facilitate azeotropic distillation. In this step, m-xylene was employed as the agent for the heterogeneous removal of the reaction product, EG. [15] This process continued until there was no noticeable separation of EG. The resultant product was subsequently utilized without undergoing any further purification.

2.1- Production of unsaturated polyesters (UPeN) based on PET product glycolys

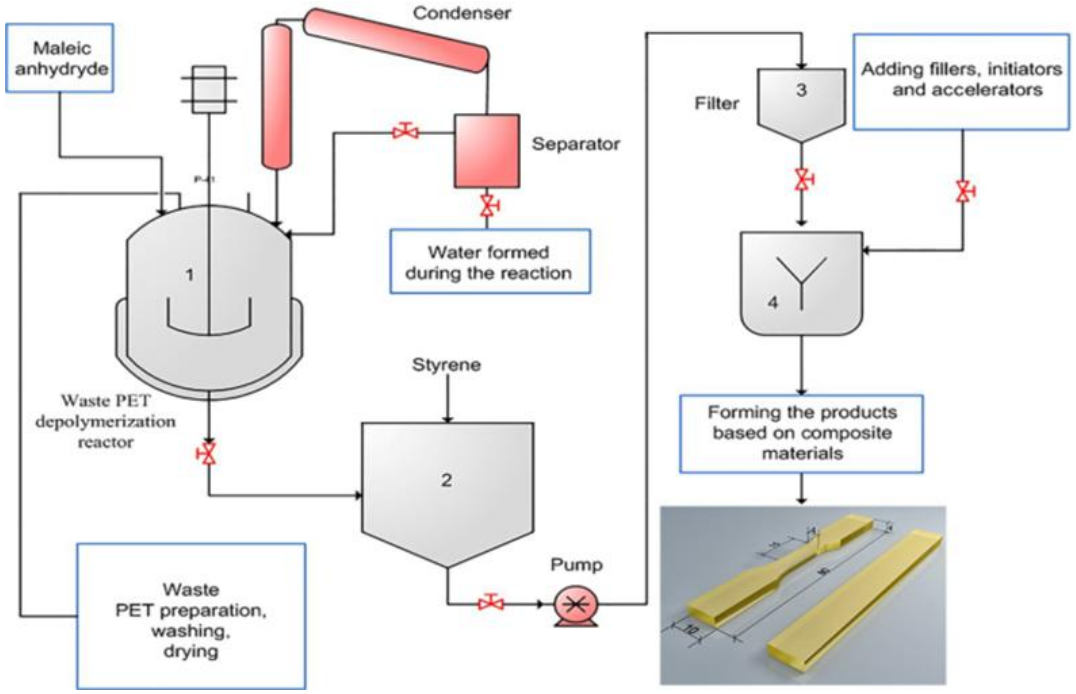
The production of unsaturated polyesters (UPeN) through glycolysis of PET products has been elaborated in recent literature. The process begins by cooling the reaction mixture to 90 ºC, after which maleic anhydride (MA) and hydroquinone (HQ) are introduced under an inert atmosphere. The mixture is then heated to 115 ºC for one hour, followed by a continuous temperature increase at a rate of 15 ºC per hour. Upon reaching 150 ºC, xylene is added to facilitate the removal of water via binary azeotrope, thereby providing a driving force for the reaction to reach its endpoint at 210 ºC. Once the reaction is complete, the resin is cooled to 120 °C and hydroquinone dissolved in absolute ethanol is added to the mixture. Low boiling compounds are eliminated through careful vacuum distillation over the course of an hour. The resin is then cooled to 90 ºC and styrene is incorporated (40 wt.%) to achieve product homogeneity. Depending on the method of glycolysis applied—whether the classical method (referred to as UPe1) or the EG azeotropic removal method (termed UPe2)—the final unsaturated polyester product differs.

2.2- Preparation of nanocomposites based on UPeN and fumed silica

The section describes the preparation of nanocomposites designated as UPeN/SiO2R812S(n), which involve the combination of UPeN resin and fumed silica (Aerosil R812S). The manufacturing process begins by carefully blending specific quantities of UPeN resin and nanofillers, with the index 'N' indicating the type of resin used and 'n' representing the weight percentage of Aerosil R812S added. The weight percentages range from 0.1% to 2.0%.

Homogenization of the fumed silica with UPeN, which contains 60% resin in styrene, was conducted using both a modified laboratory homogenizer and an ultrasonic bath, employing Bandelin electronic equipment from Berlin, Germany, operating at a power of 120W and a frequency of 35 kHz. Following the homogenization process, both the pure UPeN and the nanocomposites UPeN/SiO2R812S(n) underwent a curing process. [15] This curing utilized methyl ethyl ketone peroxide (MEKP) at a concentration of 1% as an initiator and cobalt octoate (Co-oct) at 0.5% as an accelerator.

The resulting uncured polymeric dispersion was subjected to high-speed homogenization at 800 revolutions per minute (rpm) before being placed in a polytetrafluoroethylene (PTFE) mold to facilitate the completion of the curing reactions, which is outlined in the accompanying technological scheme (referred to as Scheme 1).



Scheme 1 ; Schematic overview of the UPe and nanocomposite production.

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2.3- Characterization methods

The characterization methods employed in the study involved several analytical techniques. Fourier Transform Infrared (FTIR) spectra were recorded using a Bomem MB-102 spectrometer over a range of 400-4000 cm-1, with a resolution set at 4 cm-1. Proton (1H) and Carbon (13C) Nuclear Magnetic Resonance (NMR) spectra were obtained in deuterated chloroform (CDCl3) on a Varian-Gemini 200 spectrometer, with operational frequencies of 200 MHz for 1H NMR and 50 MHz for 13C NMR. Elemental analyses utilized a Vario EL III Elemental analyzer. The hydroxyl value (HV) was determined using a conventional method involving acetic anhydride and pyridine, as per ISO 4326:1992. [19] The acid value (AV) was assessed according to the ASTM D3644 [20] standard. Furthermore, the number average molecular weight was calculated using an undisclosed equation referenced as eq. (1).

$$M_n = \frac{2.56100}{AV+HV} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Iodine value was measured using the Wijs method, providing a quantitative assessment of unsaturation in the sample. The viscosity of a 60 wt.% styrene solution of UPeN was evaluated at 25 °C, utilizing Ford viscosity cup 4 as per ASTM D1200 standards. The gel time for the samples was determined by measuring the cure exotherm in accordance with ASTM D 2471-99, [21] which reflects the onset of curing. Furthermore, uniaxial tensile tests of standard cured samples were conducted using an AG – X plus Universal testing machine from Shimadzu, following ASTM D882 guidelines. [22] It is noteworthy that all mechanical tests were carried out at room temperature with a crosshead speed set at 0.5 mm/min, ensuring consistency and accuracy in measuring material properties.

3. Result and discussion

3.1 -Analysis of FTIR spectra of glycolized products and UPeN reveals the functional groups on the polyester chains in waste PET glycolizates.

The analysis of FTIR spectra for glycolized products and UPeN reveals the functional groups present in the polyester chains. The glycolyzed product (designated as DPG), displayed a broad band at 3529 cm-1 corresponding to OH group stretching vibrations. Additionally, an aromatic C-H stretching vibration is noted as a shoulder around 3056 cm-1. The spectra show asymmetric and symmetric stretching vibrations of methyl and methylene groups from the modified silica and alcohol ester residue of DPG within the range of 2955 to 2869 cm-1. The ester carbonyl group stretching vibration in DPG is characterized by a band at 1725 cm-1, while the absorption bands between 1300 cm-1 and 1100 cm-1 are attributed to C-O group vibrations' asymmetric and symmetric stretching.

Vibration of the ester carbonyl group present in DPG. The main absorption bands between 1300 cm-1 and 1100 cm- 1 originate from asymmetric and symmetric stretching of C-O group vibrations.

The section discusses the characterization of waste PET glycolizates and UPe through FTIR spectroscopy. The FTIR spectra analysis revealed key functional groups within the polyester chains. Specifically, the glycolized product (DPG) displays a broad absorption band at 3529 cm-1 attributed to OH group stretching vibrations and an aromatic C-H stretching vibration evident as a shoulder peak near 3056 cm-1. Additionally, stretching vibrations of methyl and methylene groups, found in both the aliphatic moieties of modified silica and the alcohol ester residue of DPG, were noted in the spectral range of 2955 - 2869 cm-1.

The band at 1725 cm-1 is attributed to the stretching vibration of the ester carbonyl group in DPG. The primary absorption bands between 1300 cm-1 and 1100 cm-1 are related to the asymmetric and symmetric stretching vibrations of the C-O groups. In the FTIR spectrum of UPe1 resin, new bands appear at 1640 cm-1 and 981 cm-1, corresponding to the C=C stretching vibration of the benzene ring and the out-of-plane bending vibrations of a 1,2-trans disubstituted vinyl group found in fumaric acid, respectively. A sharp and moderate band at 730 cm-1 observed in both DPG and UPe1 spectra is associated with the skeletal deformation (γ(CH)) vibration of the benzene ring within the terephthalic acid ester fragment. Additionally, results from 1H and 13C NMR analysis of UPe1 are anticipated to follow.

1H NMR (CDCl3): 0.96-1.58 (m, 12H, 4xCH3), 3.98-4.67 (m, 4H, 2xCH2), 5.18-5.46 (m, 4H, 2xCOOCH2), 6.95 (s, 4H, fumaric moiety), 8.08 (s,4H, HPh); 13C NMR (CDCl3): 16.2 and 19.5 (4xCH3),62.7, 65.7-66.7, 69.2-70.3, 76.4-77.6 (CH2 carbons in DPG moiety), 127.7-128.4 (4xCPh), 133.7 (O=C-HC=CH-C=O), 133.8 (2xPh(C)-COO), 164.1 and 164.4 (O=C-HC=CH-C=O), 164.9 and 165.3 (2xPhCOO).

Similar results were found for UPe2.

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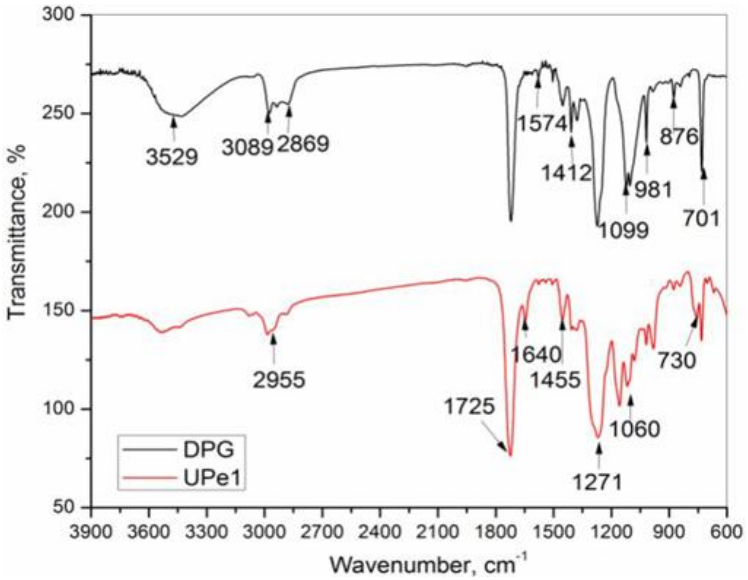


Figure 1; FTIR spectra of the glycolyzed product (named DPG; classical method) and UPe1

The study presents data on various properties of synthesized UPeN, including acid value (AV), hydroxyl value (HV), iodine value (IV), molecular weight (Mn), and viscosity, as detailed in Table 1. The results indicate that the synthesized UPeN exhibit comparable characteristics with only minor variances; UPe1 shows slightly elevated AV, HV, and viscosity values, while Mn and iodine value are slightly reduced. This structural consistency suggests that the method of depolymerizing PET waste did not significantly alter the UPeN properties. From a techno-economic perspective, a preferred method would be one that minimizes mechanical operations and equipment, aligning with classical techniques.

Table 1 ; The AV, HV, Mn and iodine value and viscosity of the synthesized UPe

Sample	AV, mgKOH/g	HV[a], mgKOH/g	Mn[b], g/mol	IV	Viscosity, s^{-1}
UPe 1	12.4	30.9	2591	42	85
UPe 2	11.2	29.6	2750	48	88

3.2 – Mechanical testing

The mechanical testing of UPeN-based nanocomposites aims to examine how the incorporation of hexamethyldisilazane-modified silica nanoparticles affects the mechanical properties of the produced nanocomposites based on UPe. [15] The study focuses on key parameters: stress at break (σb) and elongation at break (εb), with results for the UPe1 and UPe1/SiO2R812S(n) samples presented in Figure 2.

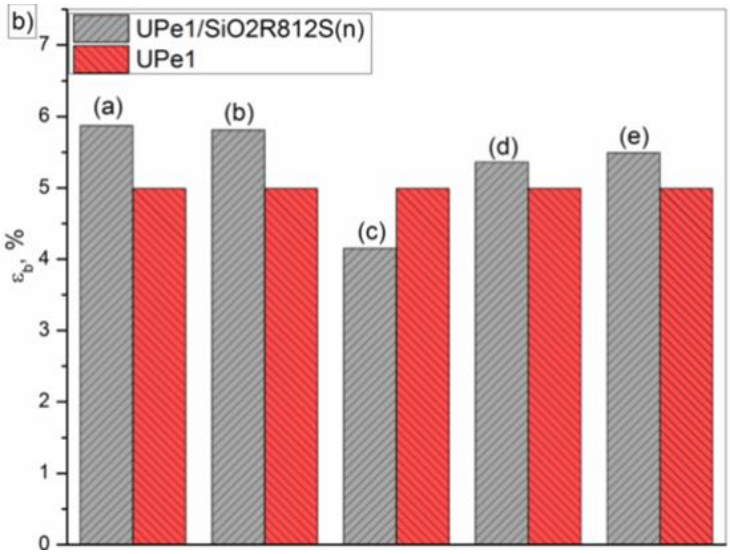


Figure 2 ;The values of a) stress at break (□b) and b) elongation at break (εb) of cured UPe1 and UPe1/SiO2R812S(n)

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Mechanical testing results reveal that all cured nanocomposites exhibit a higher stress at break compared to pure cured UPe1, with an increase linked to silica content up to 1 wt.% in UPe1/SiO2R812S(n). Beyond this point, stress at break remained constant or experienced slight reductions. The addition of more than 2 wt.% of modified silica nanoparticles complicates dispersion within the polymeric matrix. Similar trends were observed for cured UPe2 and UPe2/SiO2R812S(n), where stress at break values were elevated in the range of 1.4 - 5.8%. The greatest reinforcing effect occurred with a 1 wt.% addition of SiO2R812S, notably achieving a stress at break value of 52.6 MPa for the UPe2/SiO2R812S(d) nanocomposite. Additionally, Section 3.1 presents a comparative analysis of the structural characterization of the produced UPeN, highlighting that the EG azeotropic removal method (exp. 2.2b) offers simpler synthesis procedures while enhancing the mechanical properties of UPe2/SiO2R812S(n) derived nanocomposites. Consequently, a techno-economic analysis was conducted focusing on UPe2 resin production.

3.3 - Techno-economic analysis of UPe2 resin production

The techno-economic analysis of UPe resin production, particularly from waste PET and silica nanoparticles, is outlined as a multifaceted process encompassing capital and maintenance/operational (MO) costs. The analysis begins with the conceptual design of processing plants, which generates essential data for calculating capital investment, including costs associated with equipment, construction, and installation. Moreover, the MO costs pertaining to various UPe production technologies, such as chemicals, labor, and energy, exhibit significant variability. Consequently, the study emphasizes the identification of key influencing factors to ensure robust assessments without compromising their validity.

Techno-economic analysis of UPe2 resin production was conducted to assess profitability and economic benefits. This analysis included calculations of monthly fixed and variable costs, alongside the breakeven point, focusing on a production plant with a capacity of 5.6 tons per day (2055 tons per year). The planned capacity aligns with market demands in Serbia. Relevant costs and the breakeven point are detailed in Table 2, emphasizing profitability as a key factor for successful production implementation.

Table ; Monthly fixed and variable capital costs of UPe production

Monthly fixed costs (€)		**Monthly variable costs 5.6t\day (€)**	
Constructions		**Raw materials** (€)**	**207690**
Funds for the operation*	1776	Fuels	170
Light energy	712	Electric power for the reactor	3000
Work force	8000	Transport	1000
Sales and marketing expenses	1500	Packaging	10100
Other fixed expenses	350		
Bookkeeping and maintenance	1000		
Research and development	1500		
Total fixed costs (€)	15254	Total variable costs(€)	221960
The breakeven (monthly turnover) (€)			237214
Daily turnover (profitability) (€)			7907
Daily turnover (planned) (€)			10325
Profit per month			72540
Investment in business	Own funds		300000
	Credit		200000

The presented financial overview details the costs associated with various components necessary for a processing operation, totaling €509,240. This includes key equipment such as a reactor (€279,240), two large tanks (200 t, €80,000), a pump (€2,000), decanting tank (€2,000), transformer substation (€2,000), cooling tower

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(€10,000), fire protection system (€50,000), wastewater treatment setup (€10,000), a compressor (€20,000), two smaller tanks (100 t, €30,000), and a centrifugal pump (€4,000). The operation funds have an amortization period of 20 years, while the buildings' amortization is set for 50 years. Additionally, the cost of raw materials is outlined: Waste PET at €400/t, DPG at €2,000/t, and AMK at €1,300/t.
Economic benefits from implementing UPe technology include lower costs due to the use of raw materials like PET glycolizates. The total monthly fixed and variable costs for UPe production are estimated at €237,214. The breakeven point for UPe technology indicates that a daily revenue of €7,907 is required to achieve profitability in polyester production.

Table 3 ; Cumulative net of UPe production for period of 18 months (€)

	I quarter	**II quarter**	**III quarter**	**IV quarter**	**V quarter**	**VI quarter**
Income	60968.9	677423.3		836325	929250	929250
Fixed costs + variable costs	447171	513759		646935	713523	713523
Financing costs						
Profit	447171	513759	580347	646935	713523	713523
Reduction of financial Obligations	447171	513759	580347	646935	713523	713523
Cash flows	447171	513759	580347	646935	713523	713523
Cash balance	447171	513759	580347	646935	713523	713523
Total cash flows	447171	513759	580347	646935	713523	713523
Net present value (NVP)	126643	125270	130995	144176	165196	161955
Total net present value	357835					
Invested assets	300000					
Profit	554237					

The predicted average selling price for UPe resin stands at about €1.84/kg, allowing for a daily earning potential of €10,325 and a monthly profit of €72,540. Additionally, the cumulative net value of UPe production over an 18-month period is detailed in Table 3.
From the analysis of UPe technology production, positive net present value (NVP) was reported throughout the study period (quarters I to VI), with cumulative NVP reaching €126,643 over 18 months, indicating economic viability. The total fixed and variable monthly costs associated with UPe technology yielded profits in every quarter. The technology is deemed a viable alternative for UPe production due to its environmental benefits and lack of secondary by-products. A comparative cost analysis reveals that UPe based on DPG and MA in the Serbian market is priced above €2/kg, whereas the UPe2 resin derived from waste PET is approximately €1.84/kg, suggesting cost-effectiveness. Differences in capital costs for UPe with similar properties are negligible for techno-economic analysis. Additionally, UPe production contributes an economic advantage through waste PET azeotropic glycolysis, releasing an equimolar amount of ethylene glycol (EG), with approximately 0.68 tons of EG separated during daily production (5.6 tons/day). EG is a valuable by-product utilized in the commercial synthesis of PET and in various applications, including antifreeze, coolants, and HVAC systems.

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Table 4 ; Monthly fixed and variable capital costs of commercial UPe production

Monthly fixed and variable costs (5.6 t/day), €	
Raw materials	307260
Fuels	170
Electric power for the reactor	3000
Transport	1000
Packaging	10100
Total variable costs (€)	321530
Total fixed costs (€)	15254
The breakeven monthly turnover (€)	336784
Daily turnover (€)	11226

From a techno-economical perspective, the addition of silica to products increases raw material costs, contributing approximately 1 wt.% to the purchase cost, which is priced at 1500 €/t. Consequently, the recalculated cost of the resulting nanocomposite reflects a marginal increase of about 15 €/t for each 1 wt.% of nanosilica added, which has a minimal impact on market pricing. This analysis indicates that the market value of UPe has been validated, enhancing its competitiveness beyond just lower pricing and product quality, by offering a wide variety of market products derived from UPe.

4 – Conclusion

This study highlights the environmental and economic benefits of recycling polymeric materials, particularly PET (polyethylene terephthalate), to mitigate pollution by decreasing the demand for new raw materials, conserving energy, reducing greenhouse gas emissions that contribute to climate change, and lowering costs associated with waste raw materials. The primary objective was to explore the feasibility of producing polyester resins through the chemical depolymerization of waste PET. Among the evaluated resins, UPe1 and UPe2, UPe2 emerged as the favored material due to its superior product properties and its alignment with the techno-economic criteria necessary for practical implementation.

The analysis revealed positive NVP (net present value) results in a quarterly overview, establishing that the proposed UPe production technology is economically viable. This viability is largely attributed to reduced costs related to the plant, construction materials, and the waste PET itself, which plays a significant role in the overall financial structure. Furthermore, the integration of hexamethyl-disilazane modified silica nanoparticles at a concentration of 1 wt.% in the composite materials was shown to enhance the physico-mechanical properties without adversely affecting the economic feasibility of the production technology. Thus, the research advocates for the utilization of recycled PET in the development of UPe-based materials, affirming its practicality and potential to contribute positively to eco-sustainable manufacturing practices.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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