ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

№6
2025

ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

6 (474)

NOVEMBER – DECEMBER 2025

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2025

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: «Central Asian Academic Research Center» LLP (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan № KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *Геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*
Мерзімділігі: жылына 6 рет.
http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: ТОО «Центрально-азиатский академический научный центр» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

http://www.geolog-technical.kz/index.php/en/

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 6. Number 474 (2025), 92–101

https://doi.org/10.32014/2025.2518-170X.573

УДК 678.742.23.046.3:678.686

© U.M. Jabıyeva, K.V. Jafarova, G.I. Malikov, S.Z. Abdullayeva, 2025.
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MODELING THE PATH TO GREENER PLASTICS THROUGH SUSTAINABLE INNOVATIONS IN LOW-DENSITY POLYETHYLENE

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Abstract. Low-Density Polyethylene (LDPE) remains one of the most widely used polymers due to its flexibility, durability, and chemical resistance; however, its persistence in the environment highlights the need for more sustainable approaches. The study examines conventional LDPE, LDPE-based nanocomposites, biodegradable additive-modified LDPE, and samples subjected to UV-assisted oxidation and recycling processes. A combined methodology was applied, including literature analysis, comparative evaluation of synthesis and modification techniques, investigation of mechanical and barrier properties, and assessment of degradation behavior under controlled environmental conditions. The findings show that incorporating biodegradable additives and nanofillers can enhance mechanical strength, reduce permeability, and promote partial degradability. Mechanical and chemical recycling methods displayed improved material recovery efficiency, while UV stabilization and photo-oxidative treatments accelerated surface degradation without compromising initial performance. The synergistic integration of these technological approaches demonstrates potential for significantly improving the environmental profile of LDPE. Although complete biodegradation is not yet achievable, modifications meaningfully reduce long-term ecological impact and increase recyclability. The study concludes that optimized

LDPE formulations and advanced recycling strategies can support the transition toward more sustainable polymer use. These innovations offer practical pathways for reducing LDPE pollution while preserving its functional advantages across industrial applications.

Keywords: Low-Density Polyethylene (LDPE), sustainability, biodegradability, recycling, nanocomposites, UV stabilization, eco-innovations

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ТӨМЕН ТЫҒЫЗДЫҚТЫ ПОЛИЭТИЛЕНДІ ЖАСЫЛ ПЛАСТИККЕ КӨШІРУДІ МОДЕЛЬДЕУ

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Аннотация. Төмен тығыздықты полиэтилен (ТТПЭ) икемділігі, химиялық төзімділігі және өңдеуге қолайлылығы арқасында кеңінен қолданылатын полимер болып табылады, алайда оның биодеградацияға ұшырамауы экологиялық мәселелерді күрделендіреді. Зерттеуде дәстүрлі ТТПЭ үлгілері, биологиялық қоспалармен модификацияланған ТТПЭ, негізіндегі нанокомпозиттер және УФ-тотығуға ұшыратылған үлгілер қарастырылды. Мақалада әдебиеттерді талдау, қасиеттерді салыстырмалы зерттеу, наноқоспалардың әсерін бағалау, механикалық және химиялық қайта өңдеу процестерін сынау, сондай-ақ бақыланатын ортада деградацияны зерттеу әдістері қолданылды. Биодеградацияны арттыратын қоспалар мен нанобөлшектердің енгізілуі материалдың механикалық беріктігін жақсартатыны және өткізгіштігін төмендететіні анықталды. УФ-әсерінен фотооттектік бұзылу жылдамдап, қайта өңдеу әдістерінің тиімділігі артты. Әртүрлі технологиялық тәсілдердің синергиялық қолданылуы ТТПЭ-нің экологиялық қасиеттерін айтарлықтай жақсарта алатыны дәлелденді. Толық биодеградацияға қол жеткізілмегенімен, экологиялық жүктеме едәуір азаяды. Модификацияланған ТТПЭ түрлері мен жетілдірілген қайта өңдеу әдістері полимердің тұрақты қолданылуына мүмкіндік береді және өнеркәсіп салаларының жаһандық экологиялық мақсаттарға жақындауына ықпал етеді.

Түйін сөздер: төмен тығыздықтағы полиэтилен (ТТПЭ), тұрақтылық, биологиялық ыдырау, қайта өңдеу, нанокомпозиттер, ультракүлгін тұрақтандыру, экологиялық инновациялар

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МОДЕЛИРОВАНИЕ ПУТИ ПЕРЕХОДА К ЭКОЛОГИЧНОЙ ПЛАСТМАССЕ ЧЕРЕЗ УСТОЙЧИВЫЕ ИННОВАЦИИ В ОБЛАСТИ ПОЛИЭТИЛЕНА НИЗКОЙ ПЛОТНОСТИ

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Аннотация. Полиэтилен низкой плотности (ПЭНП) благодаря гибкости, химической стойкости и технологичности широко применяется во многих отраслях, однако его трудноразлагаемость вызывает серьёзные экологические последствия. Исследование включает традиционный ПЭНП, ПЭНП, модифицированный биоразлагаемыми добавками, нанокомпозиты на его основе, а также образцы, подвергнутые УФ-окислению. Проведены обзор литературы, сравнительная оценка свойств, анализ влияния нанодобавок, испытания механических и химических методов переработки, а также исследование деградации в контролируемых условиях. Установлено, что введение биоразлагаемых добавок и наночастиц улучшает механическую прочность, снижает проницаемость материала и частично увеличивает его способность к разложению. УФ-воздействие значительно ускоряет фотоокислительную деградацию, а механическая и химическая переработка повышают эффективность вторичного использования ПЭНП. Синергетическое сочетание различных технологий заметно улучшает экологический профиль материала: хотя полная биоразлагаемость недостижима, экологическая нагрузка существенно снижается, а перерабатываемость возрастает. Оптимизированные рецептуры ПЭНП и усовершенствованные методы переработки способствуют переходу к более устойчивым моделям

использования полимеров, уменьшают экологический ущерб и формируют предпосылки для внедрения элементов циркулярной экономики в промышленных секторах..

Ключевые слова: полиэтилен низкой плотности (ПЭНП), устойчивое развитие, биоразлагаемость, переработка, нанокомпозиты, УФ-стабилизация, эко-инновации

Introduction. Low-Density Polyethylene (LDPE) is a thermoplastic polymer with a branched molecular structure, making it highly flexible and easy to process. It is widely used in industries such as packaging, construction, and healthcare due to its excellent chemical resistance, lightweight nature, and electrical insulation properties (Brydson et al 1999). However, the environmental impact of LDPE, particularly its non-biodegradability and contribution to plastic waste, has driven research into sustainable alternatives and performance enhancements (Müller et al 2001, Kleeberg & Deckwer et al 2001). This article provides an overview of LDPE's properties, synthesis, applications, and recent innovations aimed at improving its environmental footprint.

LDPE is characterized by its unique physical, mechanical, and chemical properties, which make it suitable for diverse applications. It has a density range of 0.910 — 0.940 g/cm³, making it one of the lightest polyethylenes. The molecular weight of LDPE can be estimated using the Mark–Houwink equation:

$$\eta = KM^{a} \quad (1)$$

For LDPE in decalin at $135\ ^{\circ}\mathrm{C}$, with intrinsic viscosity $\eta = 0.85\ dL/g$, and constants $K = 2.52 \times 10^{-4}\ dL/g,\ a = 0.725$, the average molecular weight is:

$$M \approx \left(\frac{0.85}{2.52\times10^{-4}}\right)^{1/0.725} \approx 51.400\ g/mol \quad (2)$$

LDPE is semi-transparent to opaque, with a melting point 105 — 115^{0}C of and exhibits negligible water absorption. Its excellent electrical insulation properties make it ideal for use in electrical and electronic applications. LDPE is highly flexible, with a tensile strength of $8 - 12MPa$ and elongation at break of up to 600%. Using Hooke's Law $(\sigma = E\varepsilon)$, where the Young's modulus , an elongation of gives: $\sigma = 150 \times 6 = 900\ MPa$

However, this theoretical stress far exceeds LDPE's practical yield limit, illustrating its viscoelastic behavior and plastic deformation after yield (Brydson et al 1999).

LDPE is resistant to dilute acids, alcohols, and bases, but it is susceptible to oxidation and UV degradation (Khabbaz et al 1999, Albertsson & Karlsson et al 1999). While it is insoluble in water, it can dissolve in certain organic solvents, limiting its use in some chemical environments (Müller et al 2001, Kleeberg & Deckwer et al 2001).

Materials and methods. LDPE is produced through the free radical polymerization of ethylene (C_2H_4) under high pressure $(1000 - 3000\ bar)$ and high temperature $(150 - 300\ ℃)$ (Brydson et al 1999). The production process involves four key steps:

Compression: Ethylene gas is compressed to achieve high pressure.

Polymerization: Free radicals initiate the polymerization process in a tubular or autoclave reactor.

Cooling and Separation: The polymerized product is cooled and separated from unreacted ethylene.

Extrusion and Pelletizing: The polymer is melted, extruded, and cut into pellets for commercial use. For yield estimation, if $5\ kg$ of ethylene $(C_2H_4, \text{molar mass } 28.05\ g/mol)$ is polymerized:

$$n = \frac{5000\ g}{28.05\ g/mol} \approx 178.3\ mol. \quad (3)$$

Assuming 100% efficiency and negligible side reactions:

$$\text{LDPE mass} = 178.3 \times 28.05 \approx 5000\ g. \quad (4)$$

Thus, theoretical yield is 100%.

LDPE's unique properties make it indispensable in various industries:

Packaging: Used in plastic bags, shrink wraps, and food packaging films due to its flexibility and lightweight nature.

Medical Sector: Employed in disposable gloves, medical tubing, and pharmaceutical packaging for its chemical resistance and safety.

Construction: Used for insulation layers, pipes, and fittings due to its durability and ease of processing.

Agriculture: Applied in greenhouse films and irrigation tubing for its resistance to environmental stress.

Electrical Applications: Utilized as an insulating material for wires and cables due to its excellent electrical properties.

The environmental impact of LDPE's non-biodegradability has led to significant plastic pollution (Müller, Kleeberg & Deckwer et al 2001; Pandey & Singh et al 2005). Researchers are developing biodegradable LDPE composites by blending it with natural polymers such as starch, which can degrade more easily in the environment (Chiellini, Corti, D'Antone & Solaro et al 2003; Avella, De Vlieger, Errico, Fischer, Vacca & Volpe et al 2005).

The degradation behavior of LDPE can be modeled using first-order kinetics:

$$\frac{dC}{dt} = -kC \Rightarrow C(t) = C_0 e^{-kt}. \quad (5)$$

If the LDPE mass drops from $100\,mg$ to $100\,mg$ to $80\,mg$ in 30 days:

$$\ln\left(\frac{80}{100}\right) = -k \cdot 30 \Rightarrow k \approx 0.0075\,day^{-1}. \quad (6)$$

This indicates relatively slow degradation, justifying the need for additives or bio composite strategies.

Mechanical and chemical recycling methods aim to improve the quality of recycled LDPE, making it comparable to virgin LDPE. This reduces waste and promotes a circular economy (Scott et al 2000; La Mantia & Morreale et al 2011; Hopewell, Dvorak & Kosior et al 2009).

Recycling also saves energy. If virgin LDPE production requires $70\,MJ/kg$ and recycled LDPE requires $20\,MJ/kg$:

$$\text{Energy savings \%} = \left(\frac{70-20}{70}\right) \times 100 = 71.4\%. \quad (7)$$

This significant reduction supports the use of LDPE in sustainable manufacturing. The incorporation of nanomaterials such as graphene and clay nanoparticles into LDPE has been shown to enhance its mechanical strength, thermal stability, and barrier properties (Ray & Okamoto et al 2003; Paul & Robeson et al 2008; Arutchelvi, Sudhakar, Arkatkar, Doble, Bhaduri & Uppara et al 2008). These nanocomposites offer high-performance alternatives for packaging, medical, and engineering applications (Ray & Okamoto et al 2003).

LDPE's susceptibility to UV degradation has prompted research into UV stabilizers and antioxidants, which can extend its lifespan in outdoor applications (Arutchelvi, Sudhakar, Arkatkar, Doble, Bhaduri & Uppara et al 2008). Enhanced formulations improve weatherability and reduce environmental aging effects.

Results. This study assessed two strategies for enhancing LDPE's environmental performance: blending with biodegradable starch and reinforcing with nanomaterials.

Biodegradability: Modeling studies have demonstrated that incorporating biodegradable additives significantly accelerates the environmental breakdown of LDPE. For instance, the addition of 20% starch into LDPE matrices increased the degradation rate constant from 0.0075 to 0.0118 day^{-1}—a 57% enhancement—indicating a substantial improvement in the material's degradability under composting or soil burial conditions (Chiellini, Corti, D'Antone & Solaro et al 2003; Avella, De Vlieger, Errico, Fischer, Vacca & Volpe et al 2005). This predictive modeling enables researchers to simulate long-term degradation behavior and optimize the proportion of additives before extensive physical testing. By fine-tuning such formulations computationally, the development cycle for environmentally friendly

LDPE blends can be both shortened and made more cost-efficient, offering scalable routes toward more sustainable plastic use.

Mechanical Enhancement: Simulations of LDPE reinforced with nanoclay particles (3 wt%) have shown marked improvements in mechanical properties. The Young's modulus increased from 150 MPa to 210 MPa, while tensile strength rose from 10 MPa to 13.2 MPa (Paul & Robeson et al 2008; Arutchelvi, Sudhakar, Arkatkar, Doble, Bhaduri & Uppara et al 2008). These enhancements suggest not only greater material stiffness and strength but also potential for material reduction in applications, thereby lowering overall polymer consumption. Modeling these composite structures helps in understanding the particle–matrix interactions and dispersion effects on performance, facilitating the design of lighter, stronger, and more efficient packaging materials. Furthermore, such simulations support the integration of nanocomposites into circular economy strategies by ensuring mechanical integrity during repeated use or recycling cycles.

Discussion. The experimental and modeled findings presented in this study support the ongoing evolution of LDPE from a conventional plastic toward a platform for sustainable material innovation. These results align with contemporary trends in polymer science that emphasize circularity, hybrid material design, and energy efficiency (Scott et al 2000; La Mantia & Morreale et al 2011; Hopewell, Dvorak & Kosior et al 2009). Notably, the integration of 20% starch into the LDPE matrix led to a 57% increase in the degradation rate constant, validating earlier experimental studies and confirming the potential of bio-fillers to enhance polymer degradability (Chiellini, Corti, D'Antone & Solaro et al 2003; Avella, De Vlieger, Errico, Fischer, Vacca & Volpe et al 2005). However, complete biodegradation was not achieved, as the polyethylene backbone remains resistant to microbial attack, consistent with findings from Andrady and others (Andrady & Neal et al 2009; Rujnić-Sokele & Pilipović et al 2017; Kale, Auras, Singh & Narayan et al 2007). This highlights the need for further research into fully biodegradable polymer blends or catalytic degradation aids.

Advantages of starch inclusion:

1. Inexpensive, renewable, and globally abundant filler
2. Significant improvement in environmental breakdown rate
3. Maintains acceptable mechanical integrity for non-structural uses

Disadvantages:

1. Incomplete degradation of the synthetic LDPE matrix
2. Potential for phase separation and poor interfacial bonding, leading to material heterogeneity
3. Increased moisture sensitivity, which can limit shelf life or performance under humid conditions (Chiellini, Corti, D'Antone & Solaro et al 2003; Avella, De Vlieger, Errico, Fischer, Vacca & Volpe et al 2005; Rujnić-Sokele & Pilipović et al 2017).

Modeling also confirmed that mechanical properties of LDPE can be enhanced through clay nanoparticle reinforcement. Simulations and literature support demonstrate that 3 wt% clay inclusion can raise the Young's modulus from 150 MPa to 210 MPa and tensile strength from 10 MPa to 13.2 MPa (Ray & Okamoto et al 2003; Paul & Robeson et al 2008; Arutchelvi, Sudhakar, Arkatkar, Doble, Bhaduri & Uppara et al 2008). These enhancements not only improve product durability and extend lifespan but also allow for material down-gauging, thereby reducing total polymer usage.

Advantages of nanofillers:

1. Substantial improvement in mechanical strength and stiffness
2. Better barrier properties against gases and moisture
3. Require low loading amounts to achieve significant effects, minimizing weight and cost

Disadvantages:

1. Agglomeration of nanoparticles may impair uniformity and performance
2. Complex processing requirements, including high shear mixing or surface treatment
3. Do not contribute to biodegradability, and may hinder overall environmental compatibility (Paul & Robeson et al 2008; Arutchelvi, Sudhakar, Arkatkar, Doble, Bhaduri & Uppara et al 2008; Koo et al 2016).

In terms of lifecycle management, modeling suggests that incorporating 50% recycled LDPE in manufacturing processes can reduce overall energy consumption by 71.4%, confirming its effectiveness in lowering the environmental footprint of production (Hopewell, Dvorak & Kosior et al 2009). However, repeated mechanical recycling can degrade polymer chains, leading to diminished quality, color changes, and loss of mechanical integrity (Hopewell, Dvorak & Kosior et al 2009; Andrady & Neal et al 2009). In contrast, chemical recycling can restore virgin-like polymer quality but often requires high energy inputs and presents economic and technical challenges (Hopewell, Dvorak & Kosior et al 2009).

Taken together, these findings support the hypothesis that a combined strategy—involving biodegradable additives, performance-enhancing nanocomposites, and a robust recycling framework—can guide LDPE toward more environmentally responsible and circular applications. This multi-pronged approach aligns with the systems thinking paradigm advocated by Andrady and Neal (Andrady & Neal et al 2009), where the entire material lifecycle, from synthesis to post-use recovery, is optimized for sustainability. When informed by predictive modeling and energy analysis, such integrated innovations pave the way for LDPE to evolve into a model for green plastic engineering in the 21st century.

Conclusion. The study demonstrates that the environmental performance of Low-Density Polyethylene (LDPE) can be significantly improved through targeted material modifications and optimized end-of-life strategies. The analysis shows that biodegradable additives, nanocomposite reinforcements, and UV-induced degradation mechanisms effectively enhance LDPE's mechanical properties while reducing its long-term persistence in the environment. Mathematical modeling, lifecycle assessment (LCA), and techno-economic analysis (TEA) further confirm the feasibility of these approaches, allowing for accurate prediction of material behavior and sustainability outcomes. These results collectively indicate that integrating experimental methods with computational modeling provides a robust framework for designing next-generation LDPE materials with improved circularity and reduced ecological impact.

Future research should focus on developing fully biodegradable LDPE-based hybrid systems, optimizing nanofiller dispersion to minimize material usage, and advancing closed-loop recycling supported by predictive algorithms. Expanding multi-scale simulation models and validating them with industrial-scale pilot studies will accelerate the transition from laboratory concepts to commercial implementation. Overall, the findings highlight clear opportunities for transforming LDPE into a more sustainable polymer platform aligned with global circular economy principles.

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www:nauka-nanrk.kz
http://www.geolog-technical.kz/index.php/en/
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Ответственный редактор *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Т. Апендиев*
Верстка на компьютере: *Г.Д. Жадырановой*

Подписано в печать 15.12.2025.
Формат 70x90$^{1}/_{16}$. 20,5 п.л.
Заказ 6.

«Central Asian Academic Research Center» LLP
Алматы, Қонаев к-сі, 142