

stress factors such as drought and temperature fluctuations. Potassium also contributes to the improvement of crop quality, including grain filling, sugar accumulation, and resistance to diseases and pests. Therefore, balanced application of nitrogen, phosphorus, and potassium fertilizers is essential for achieving optimal plant nutrition and sustainable crop production.

Numerous studies indicate that the application of balanced NPK fertilizers significantly increases crop productivity. Under conditions of the Steppe zone, the use of scientifically justified fertilizer rates can increase yields by 20–40% compared to unfertilized control variants. In addition, balanced fertilization contributes to maintaining an optimal nutrient regime in soil and preventing soil degradation processes associated with nutrient depletion [2].

At the same time, environmental aspects of fertilizer application should also be taken into account. Improper use of fertilizers, especially excessive nitrogen application, may cause nitrate leaching into groundwater, soil acidification, and disturbance of ecological balance in agroecosystems. Therefore, the rates and methods of fertilizer application should be based on agrochemical soil analysis, crop requirements, and climatic conditions of the region.

In conclusion, mineral fertilizers play a crucial role in maintaining and improving the fertility of chernozems in the Southern Steppe of Ukraine. Their effective use requires scientifically based fertilizer rates, systematic soil monitoring, and integration with organic fertilization systems. The development of optimized fertilization systems under conditions of climate change and limited moisture availability is an important direction for further scientific research in agronomy and agrochemistry.

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PROSPECTS FOR MICROBIAL DEGRADATION OF SYNTHETIC POLYMERS

У статті досліджується критична проблема накопичення пластикових полімерів у біосфері та розглядаються біотехнологічні стратегії їх переробки. Проведено аналіз еволюційної адаптації мікроорганізмів до синтетичних субстратів, механізмів роботи ферментативних систем та роль генної інженерії у створенні високоефективних штамів-деструкторів.

Ключові слова: біодеградація, антропогенне навантаження, ензими, *Ideonella sakaiensis*, ПЕТ-гідролази, мікробна конверсія, полімери, ПЛА.

This article examines the critical issue of the accumulation of plastic polymers in the biosphere and explores biotechnological strategies for their degradation. It analyses the evolutionary adaptation

of microorganisms to synthetic substrates, the mechanisms underlying enzymatic systems, and the role of genetic engineering in the creation of highly efficient degrading strains.

Keywords: biodegradation, anthropogenic load, enzymes, *Ideonella sakaiensis*, PET hydrolases, microbial conversion, polymers, PLA.

It is hard to imagine any area of our daily lives or industry where synthetic polymers do not dominate. Their exceptional strength, inertness and low production costs made plastic the triumph of engineering thought in the last century, but these very advantages have now turned into an environmental disaster. The problem is that humanity has learnt to synthesise materials faster than nature can develop the mechanisms to break them down. The carbon-carbon bonds that form the backbone of most plastics are too stable for the ordinary enzymatic systems that have evolved in ecosystems over millions of years. As a result, we are witnessing an alarming situation: waste does not disappear, but merely breaks down into microplastics, seeping into groundwater and becoming part of food chains. Traditional approaches - from landfill to incineration - merely mask the problem or create new risks in the form of toxic emissions [5].

The process of biodegradation is not simply the breakdown of material, but a sophisticated biochemical strategy employed by microorganisms. It all begins with colonisation: bacteria or fungi must «attach» themselves to the slippery and typically hydrophobic surface of the plastic. To do this, they form complex biofilms and secrete surfactants that help the microbes literally «wet» the inert material. Once the foothold is established, extracellular enzymes - true biochemical catalysts - come into play. They act as high-precision tools, breaking down long polymer chains into small oligomers and monomers. Since a microorganism's cell cannot absorb a huge plastic molecule whole, the very efficiency of these «external» enzymes is the decisive factor. Only after the chains have been broken down into small fragments can the bacterium assimilate them, using the carbon from the plastic for its own metabolic processes. The end result of this metabolic pathway is mineralisation - the complete conversion of the former waste into water and carbon dioxide [6,8].

The story of the bacterium *Ideonella sakaiensis* marked a genuine scientific breakthrough in this field. Its discovery in 2016 near a Japanese PET recycling plant demonstrated the incredible resilience of life. This microorganism has not merely learnt to survive amidst plastic; it has evolved to the point where polyethylene terephthalate has become its primary food source. The key to this was a specific enzyme, PETase, which is capable of recognising the structure of the synthetic polymer even at moderate temperatures. This discovery proved that nature has already begun to adapt to the «plastic age», and our task as scientists is to help this process scale up. Although natural strains are currently working too slowly to clean up the planet within a year, they have given us a genetic blueprint that we can refine [1,2].

However, one should not think that biodegradation is an easy path. In practice, we face serious barriers, the main one being the crystallinity of plastic. The molecules in packaging or a bottle are often packed into such dense structures that enzymes simply cannot access the chemical bonds. Furthermore, most plastics «fear» water, which creates a conflict with the aquatic environment in which bacteria live. To overcome this resistance, biotechnology employs a combination of methods: from thermal processing, which renders the plastic amorphous and brittle, to chemical modification of the surface. Even temperature poses a challenge, as most natural enzymes are destroyed under the conditions required to soften polymers [2].

This is where the tools of genetic engineering and bioinformatics come into play. Today, we are not merely observing nature, but acting as its architects. Using computer modelling, we redesign the structure of enzymes, making them more thermostable and aggressive towards plastic. Directed evolution allows us to cover in the laboratory in a few months a path that would have taken nature millennia. In addition to creating individual «super-bacteria», we are developing synthetic microbial consortia - teams of different species, where each performs its own part of the work: one breaks down the crystal lattice, another cleaves oligomers, and a third utilises the by-products. Such systems fit perfectly into the concept of bioreactors, where plastic is converted into valuable raw materials for new manufacturing processes [3,7].

It is important to emphasise that biotechnology is not a panacea for all environmental ills. We

cannot simply «flood» the oceans with bacteria and continue to consume plastic at the same rate. A systematic approach is needed, combining biodegradation with a shift to bioplastics such as polylactic acid (PLA). These materials are designed from the outset to be «microbe-friendly», allowing them to break down rapidly under industrial composting conditions. The combination of smart design of new materials and powerful biocatalysts for processing old waste is the only way to restore the ecological balance [4].

In conclusion, I would like to note that the role of the modern biotechnologist is that of a mediator between technological progress and the planet's biological sustainability. Research into how the micro-world colonises new, artificially created ecological niches provides us with a unique toolkit for global clean-up. The biodegradation of plastic is not merely a scientific trend, but a prerequisite for survival in the technosphere. By understanding biochemical processes at the molecular level, we are transforming the waste problem into a managed recycling cycle. And although the path from the laboratory test tube to a large-scale bio-recycling plant is fraught with difficulties, every successfully broken-down polymer chain brings us closer to a world where plastic will cease to be a curse and become a resource.

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