**Environmental requirements for packaging materials of food and industrial products in the context of energy efficiency of production**

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***Abstract.*** This article examines environmental requirements for packaging materials used for food and industrial products in the context of sustainable development and increasingly stringent environmental regulations. The article analyzes the main types of packaging materials—polymers, paper and cardboard, glass, metal, and composites—in terms of their environmental impact throughout their entire life cycle, including production, use, processing, and disposal. Particular attention is paid to food packaging safety requirements, such as the absence of toxic substances, prevention of migration of harmful components, and compliance with sanitary and hygienic standards. It examines international environmental standards and regulatory requirements, as well as current trends toward biodegradable, recyclable, and reusable packaging. It emphasizes the need for a comprehensive approach to selecting packaging materials that ensures a balance between functional characteristics, cost effectiveness, and environmental sustainability.

**INTRODUCTION**

Priority is given to recyclable or biodegradable packaging. Manufacturers must minimize the use of difficult-to-decompose plastics and implement sustainable production and waste sorting practices.

One of the key requirements in today's environment is ensuring the recyclability of used packaging. When selecting packaging materials and containers for a specific product, manufacturers must consider this factor, which aims to reduce the negative environmental impact of the packaging after its use. Several approaches exist to address this issue: reducing packaging weight, recycling it with energy recovery through incineration, recycling, using reusable containers, landfilling, depolymerization, and thermal degradation. In some cases, edible packaging coatings can be used in the food industry. Of greatest interest today are packaging solutions that are long-lasting and self-degradable at the end of their useful life.

The growth of food production and rapid technological advances have taken transport packaging to a whole new level. This type of packaging reduces losses, preserves products in good condition for a long time, and ensures their delivery to the end consumer in an attractive form.

Synthetic polymers have become widely used as a highly effective alternative to natural materials. They possess a number of unique properties unavailable to naturally occurring raw materials.

As packaging production advances, not only do the functions it performs grow, but the requirements for its quality characteristics also become more stringent. Key ones include:

* protection of contents from external influences;
* ensuring safety during use;
* compliance with hygiene standards;
* extending the shelf life of products and preserving their consumer properties;
* compatibility with specific types of products;
* convenience in transportation and packaging.

Although polymeric materials offer a number of sanitary and hygienic advantages—they are less easily contaminated, easier to clean, and remain stable under the influence of physical factors—the potential chemical risks associated with their use must be considered.

Many polymers used in packaging contain components that can be released at various stages—during production, processing, and use. These substances can contaminate the environment, food products, and negatively impact human health. Therefore, accurate information on the sanitary and hygienic properties of polymeric materials used in packaging is essential.

In recent years, developed economies, particularly in the European Union, have significantly strengthened environmental packaging requirements for both food and industrial goods. These standards are gradually becoming mandatory. The primary goal is to minimize environmental pollution from used packaging and the substances released during its disposal, particularly during incineration.

**EXPERIMENTAL RESEARCH**

To regulate this issue, in 1994, the European Union's health authorities adopted a directive establishing mandatory environmental standards for all types of packaging. According to the directive, the mass and volume of packaging material must be minimized while maintaining the safety and reliable protection of the product. Furthermore, only minimal amounts of potentially harmful substances are permitted in packaging. Packaging must also be reusable and, at the end of its useful life, allow for the recovery of its useful components or its recycling into valuable raw materials.

Future plans include introducing a system for returning packaging from consumers back to manufacturers for reuse. The return rate is expected to approach 100%. The goal is to achieve 90% recycling and at least 60% recovery of useful components from packaging materials. Germany has achieved significant success in this area, where manufacturers are legally required to organize the collection of used packaging from consumers and retailers. This is carried out by specialized organizations, whose activities are jointly funded by interested companies. Manufacturers who pay to participate are entitled to place a green sign on their packaging—a distinctive label and marketing element.

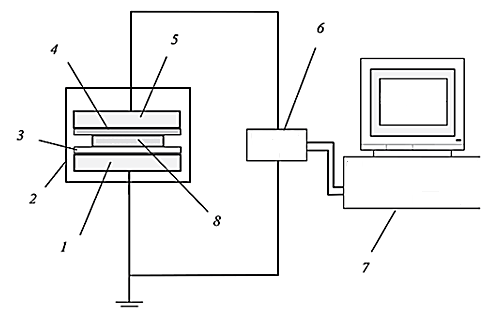
Beyond environmental concerns, stricter requirements for packaging materials are also driven by the growth of the food industry and the expanding range of products requiring special storage conditions. Each type of product requires packaging with a specific shape and set of technical characteristics.

Traditional metal cans are gradually giving way to plastic containers, vacuum packaging, and aluminum foil. New materials better preserve vitamins and ensure higher levels of hygiene. Smaller packages designed for individual consumption per meal are becoming especially popular. Although more expensive, this type of packaging will likely become the primary format for most food products in the future.

**RESEARCH RESULTS**

Methods for studying the structure and electrophysical characteristics of polymer packaging materials provide more comprehensive information than traditional methods. They are widely used, easily automated, and can be integrated into modern information systems. These methods include, in particular, thermally activated current spectroscopy (TEA), also known as electret thermal analysis (ETA). A functional diagram of the ETA setup is shown in Fig. 1.

The setup consists of a measuring cell containing two aluminum electrodes and a thermal chamber. The electrodes are insulated with heat-resistant dielectric materials (PTFE, ceramics), providing an insulation resistance of at least 1012 ohms. The system includes an automated device for software control of the thermal chamber heating (a thermostat with a thermocouple), as well as a picoammeter capable of measuring thermally stimulated current (TSC) in the range of 10−13 to 10−5 A with an error of no more than 5%. The TSC spectrum depends on the properties of the material and reflects information about the types of charge trapping centers, their energy, and the internal structure of the electret.



**Fig. 1.** Schematic diagram of the measuring complex for registration and recording of thermally stimulated currents. 1 - lower electrode (Al); 2 - detachable screen; 3 - lower gasket (Al foil); 4 - upper gasket (Teflon); 5 - upper electrode (Al); 6 - amplifier-converter; 7 - personal computer; 8 - analyzed sample.

Modern methods for studying the structure of packaging materials and their changes during use include spectroscopic technologies, such as infrared and laser spectroscopy. Among infrared methods, Fourier transform infrared spectroscopy is the most commonly used. Among laser methods, intracavity laser spectroscopy and Raman spectroscopy are in demand. Intracavity laser spectroscopy is used to detect trace amounts of elements such as sodium (Na), lithium (Li), barium (Ba), strontium (Sr), vanadium (V), and rare earth metals. Raman spectroscopy is used to analyze organic and inorganic substances in various states of aggregation. Raman spectra are used to identify substances, determine chemical bonds and functional groups, study isomers, and detect trace impurities.

In addition to identifying packaging materials based on their structure and physical and mechanical properties, thermal characteristics such as heat resistance and melting point are tested using combustion tests. These tests evaluate the material's flammability, flammability, flame character and color, and combustion product odor.

If it is difficult to determine the polymer type based on organoleptic, physical, and thermal characteristics, additional methods are used to analyze the material's chemical resistance. Such studies are particularly relevant in arbitration disputes, when it is impossible to determine the nature of the packaging by other means. To do this, the polymer is pyrolyzed, and the decomposition products are identified for the presence of characteristic atoms or groups capable of specific reactions, allowing for the detection of certain indicator effects. Simpler methods for identifying polymers rely on their solubility.

Polymeric materials have a certain level of permeability, which varies significantly depending on the chemical composition of the polymer and the characteristics of the product being packaged. When assessing the suitability of packaging made from specific polymeric materials for various products, a number of factors must be considered: product loss, changes in weight and strength characteristics of the packaging, the type of material used, permeability to aromatic substances, and changes that occur to the product during storage in polymer packaging. Standard samples tested in accordance with current regulatory documents are used to assess the chemical resistance of packaging materials.

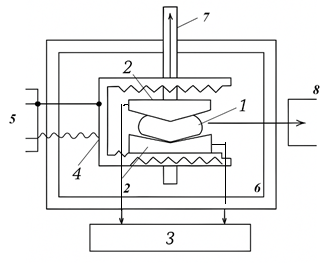
Monitoring the amount of substances that can leach from packaging is an important aspect when assessing the quality of packaging materials, as migrating components can negatively impact human health by contaminating food and the environment. Therefore, sanitary authorities establish maximum permissible concentrations of various monomers, stabilizing additives, dyes, and other chemical components contained in polymers. Particular attention is paid to methods for detecting and quantifying low concentrations of such substances. For example, luminescence analysis is used to detect derivatives of polycyclic hydrocarbons, and gas-liquid chromatography is used to determine the content of vinyl chloride monomer (up to 1 mg/kg) in polyvinyl chloride packaging, as well as to analyze benzene and its derivatives in various types of polystyrene materials.

To study so-called "active materials," which include special additives that can, under certain conditions, be released into the space within the packaging and affect the product, the isothermal depolarization method is used. It is performed using an ADS-1 disperse systems analyzer (Fig. 3.4). This method is based on the action of an electromagnetic field on a disperse system in a closed volume, followed by recording its response. This allows one to evaluate the influence of fillers on the polarization properties of the material and control the anisotropy of the packaging characteristics. This approach opens up possibilities for the creation of materials with a prolonged effect, for example, those containing antioxidants or preservatives.

Particular attention is paid to sanitary and hygienic testing when inspecting packaging materials intended for food products. Packaging must not alter the organoleptic and physiological properties of the product or release harmful substances in quantities exceeding established migration limits. Packaging materials must not contain highly toxic substances that can accumulate in the body or have specific harmful effects.

The hygienic assessment of packaging includes organoleptic, sanitary-chemical, and toxicological testing. The presence of noticeable defects and foreign odors is grounds for rejecting the material for use in contact with food.

Sanitary and chemical testing is performed by analyzing extracts obtained by holding material samples in model environments (Table 2) under specified temperature and time parameters. These extracts are used to determine the content of formulation ingredients and heavy metal levels using chemical methods.



**Fig. 2.** Schematic diagram of the experimental setup for isothermal depolarization: 1 - test sample; 2 - electrodes; 3 - ADS-1 disperse systems analyzer; 4 - heater; 5 - heater power source; 6 - thermally stabilized measuring chamber; 7 - micrometer screw; 8 - voltmeter; 9 - thermocouple.

**Table 1.** Model environments for studying food packaging materials

|  |  |
| --- | --- |
| **Product name** | **Model solutions** |
| Fresh meat and fish | Distilled water, 0.3% lactic acid solution |
| Meat, salted and smoked fish | Distilled water, 0.5% lactic acid solution |
| Milk, dairy products and dairy preserves | Distilled water, 0.3% lactic acid solution, 3% lactic acid solution |
| Cooked sausage, canned meat, fish and vegetables, pickled and fermented vegetables, pastas, etc. | Distilled water, 2% acetic acid solution containing 2% table salt; unrefined sunflower oil |
| Fruits, berries, fruit and vegetable juices, soft drinks, beer | Distilled water, 2% citric acid solution |
| Alcoholic drinks, wines | Distilled water, 20% ethyl alcohol solution, 2% citric acid solution |
| Vodka, cognac | Distilled water, 40% ethyl alcohol solution |
| Food alcohol, liqueurs, rum | Distilled water, 96% ethyl alcohol solution |
| Ready meals and hot drinks (tea, coffee, milk, etc.) | Distilled water, 1% acetic acid solution |

**Table 2.** Sanitary and hygienic safety indicators of polymer packaging materials

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Name of the product material | Controlled indicator | DMC, mg/l | MAC in drinking water, mg/l | Hazard class | MAC s.s., mg/m3 in atm/air. | Hazard class |
| 1. Polyethylene (LDPE, HDPE), polypropylene, copolymers of propylene with ethylene, polybutylene, polyisobutylene, combined materials based on polyolefins | Formaldehyde | 0.100 | − | 2 | 0.003 | 2 |
| Acetaldehyde | − | 0.200 | 4 | 0.010 | 3 |
| Ethyl acetate | 0.100 | − | 2 | 0.100 | 4 |
| Hexane | 0.100 | − | 4 | − | − |
| Heptane | 0.100 | − | 4 |  |  |
| Hexene | − | − | − | 0.085 | 3 |
| Heptene | − | − | − | 0.065 | 3 |
| Acetone | 0.100 | − | 3 | 0.350 | 4 |
| Alcohols | | | | | |
| Methyl | 0.200 | − | 2 | 0.500 | 3 |
| Propylene | 0.100 | − | 4 | 0.300 | 3 |
| Isopropyl | 0.100 | − | 4 | 0.600 | 3 |
| Butyl | 0.500 | − | 2 | 0.100 | 3 |
| Isobutyl | 0.500 | − | 2 | 0.100 | 4 |
| 2. Polystyrene block, impact-resistant | Styrene | 0.010 | − | 2 | 0.002 | 2 |
| Alcohols | | | | | |
| Methyl | 0.200 | − | 2 | 0.500 | 3 |
| Butyl | 0.500 | − | 2 | 0.100 | 3 |
| Formaldehyde | 0.100 | − | 2 | 0.003 | 2 |
| Benzene | − | 0.010 | 2 | 0.600 | 2 |
| Toluene | − | 0.500 | 4 | 0.020 | 3 |
| Ethylbenzene | − | 0.010 | 4 | 0.030 | 3 |
| 3. Polyvinyl chloride plastics | Acetaldehyde | − | 0.200 | 4 | 0.010 | 3 |
| Acetone | 0.100 | − | 3 | 0.350 | 4 |
| Vinyl chloride | 0.01 | − | 2 | 0.01 | 1 |
| Alcohols | | | | | |
| Methyl | 0.200 | − | 2 | 0.500 | 3 |
| Propylene | 0.100 | − | 4 | 0.300 | 3 |
| Isopropyl | 0.100 | − | 4 | 0.600 | 3 |
| Butyl | 0.500 | − | 2 | 0.100 | 3 |
| Isobutyl | 0.500 | − | - | 0.100 | 4 |
| Benzene | − | 0.010 | - | 0.100 | 2 |
| Toluene | − | 0.500 | 4 | 0.600 | 3 |
| Zinc (Zn) | 1,000 | − | 3 | − | − |
| Tin (Sn) | − | 2,000 | 3 | − | − |
| Dioctyl phthalate | 2.00 | − | 3 | 0.020 | − |
| Dibutyl phthalate | Not allowed |  |  |  |  |
| 4. Polyamide 6 (polycaproamide, nylon) | E-caprolactam | 0.500 | − | 4 | 0.060 | 3 |
| Benzene | − | 0.010 | 2 | 0.100 | 2 |
| Phenol | 0.050 | − | 4 | 0.003 | 2 |
| 5. Polypropylene oxide | Methyl acetate | − | − | 3 | 0.070 | 4 |
| Acetone | 0.100 | 0.200 | 3 | 0.350 | 4 |
| Formaldehyde | 0.100 | 0.100 | 2 | 0.003 | 2 |
| Acetaldehyde | − | − | 4 | 0.010 | 3 |
| 6. Polyethylene terephthalate and copolymers based on terephthalic acid | Acetaldehyde | − | 0.200 | 4 | 0.010 | 3 |
| Ethylene glycol | − | 1,000 | 3 | 1,000 | − |
| Dimethyl terephthalate | − | 1,500 | 4 | 0.010 | − |
| Formaldehyde | 0.100 | − | 2 | 0.003 | 2 |
| Alcohols | | | | | |
| Methyl | 0.200 | − | 2 | 0.500 |  |
| Butyl | 0.500 | − | 2 | 0.100 | 3 |
| Isobutyl | 0.500 | − | 2 | 0.100 | 4 |
| Acetone | 0.100 | − | 3 | 0.350 | 4 |

Health authorities regulate the maximum permissible level of total migration of substances into model environments (usually 50–60 mg/kg of product), as well as standards for individual toxic packaging components. The relevant sanitary and hygienic standards are presented in Table 1.

Toxicology tests are conducted on living subjects (microorganisms, insects, rodents, and other animals). They involve feeding test subjects extracts from packaging materials, as well as administering extracts subcutaneously or orally to study the biological effects of the substances being tested. Toxicity is assessed based on the LD50 (Latency Limit Value)—the dose required to cause lethality in 50% of test subjects over a specified period. Substances with an LD50 of less than 200 mg/kg are considered highly toxic, those with an LD50 of 200 to 1000 mg/kg are considered moderately toxic, and those with an LD50 above 1000 mg/kg are considered slightly toxic. Based on these data, permissible migration levels (PMLs) for substances from packaging into food products or model environments are established, ensuring the safety of packaged products during long-term consumption.

**CONCLUSIONS**

This article examines environmental requirements for packaging materials for food and industrial products from the perspective of energy efficiency in production and sustainable development. The analysis shows that modern packaging must meet not only sanitary, hygienic, operational, and environmental standards, but also requirements for the rational use of energy resources at all stages of the life cycle.

It has been established that the largest share of energy consumption occurs during the raw material acquisition and packaging material production stages, necessitating the implementation of energy-efficient technologies, optimization of production processes, and the use of secondary and renewable resources. For food products, a balance between environmental safety, product safety, and energy costs is a priority, while for industrial goods, reducing the energy intensity of packaging by reducing weight, increasing strength, and enabling reuse is key.

Therefore, compliance with environmental requirements for packaging materials in the context of energy efficiency in production is a key prerequisite for the development of sustainable production and supply chains. An integrated approach combining environmental and energy criteria improves product competitiveness, reduces environmental impact, and ensures long-term socioeconomic development.

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