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Food technology packaging materials, application methods, restrictions, and future potential

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Abstract. The objective of this review was to analyze modern food packaging technologies and to identify the factors that should be considered when selecting a packaging system for a specific product. The work was conducted as a structured narrative review with a clearly defined literature search strategy. Peer-reviewed publications indexed in Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley, and Google Scholar were analyzed, with emphasis on sources published between 2018 and 2026 and priority given to items bearing a DOI and directly relevant to materials intended for contact with food products. The article examines traditional monolithic and multilayer materials, modified atmosphere packaging materials, edible and biodegradable coatings, active and intelligent packaging systems, as well as antimicrobial materials. It was established that packaging effectiveness is determined not by any single barrier parameter but by the combination of properties, including oxygen and water vapor permeability, heat seal strength, product matrix characteristics, migration safety, and recyclability. The applications of form–fill–seal systems, vacuum packaging, modified atmosphere packaging, aseptic and hot filling, retort processing, edible coatings, and packaging compatible with high-pressure processing are summarized. It is shown that the most promising solutions are multifunctional systems that combine sustainable materials, active protection, indicator-based monitoring, digital traceability, and compatibility with non-thermal technologies. The practical significance of this work lies in establishing criteria for the preliminary selection of packaging during the stages of product development, process design, and risk assessment. The findings of this review can be applied in the design of packaging for meat, fish, dairy, plant-based, and ready-to-eat food products.

Keywords: packaging solutions, biodegradable materials, active packaging, intelligent packaging, modified atmosphere, migration safety, sustainability.

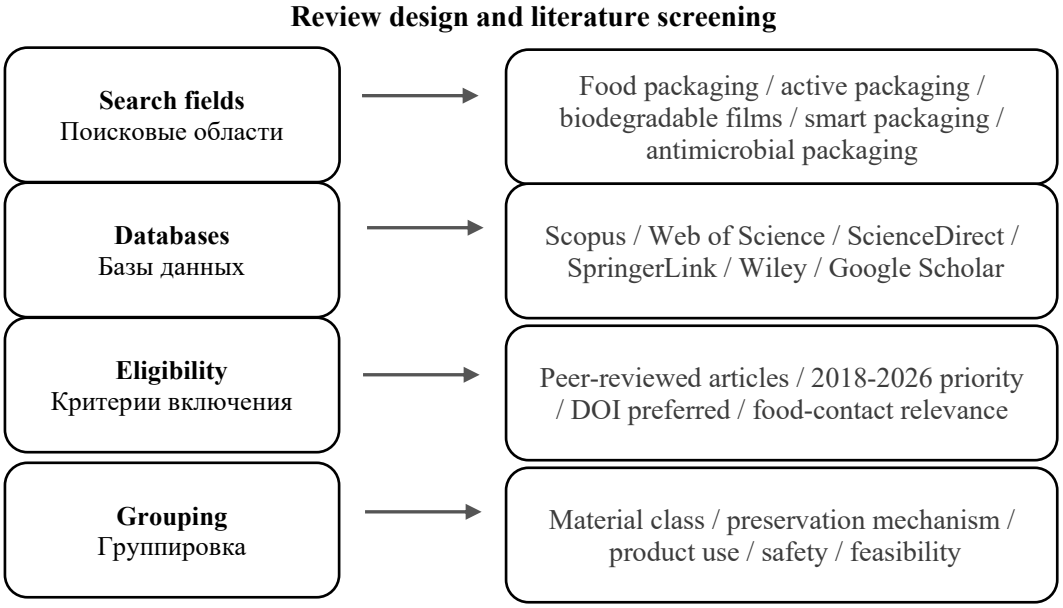


Figure 1. Scheme for source screening and grouping in the structured review

The study was conducted as a structured narrative review with a clearly defined literature-search strategy. a quantitative meta-analysis was not attempted because the selected publications

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differed substantially in material composition, food matrix, antimicrobial mechanism, analytical endpoint, and storage or packaging conditions [1]. searches were performed in Scopus, Web of Science, Sciencedirect, Springerlink, wiley, and google scholar using combinations of the terms food packaging, active packaging, antimicrobial packaging, biodegradable films, smart packaging, edible coatings, migration, food-contact materials, modified-atmosphere packaging, and microbiological safety.

Priority was given to peer-reviewed papers published mainly between 2018 and 2026, especially where the sources were indexed in major scientific databases and included DOI information. earlier publications were retained only when they were needed to explain established principles of packaging safety, waste management, active-packaging design, or microbial spoilage control. the final body of literature was grouped by material class, preservation mechanism, food-contact safety issue, antimicrobial functionality, industrial application, and direction of technological development.

Main Classes of Food Packaging Materials

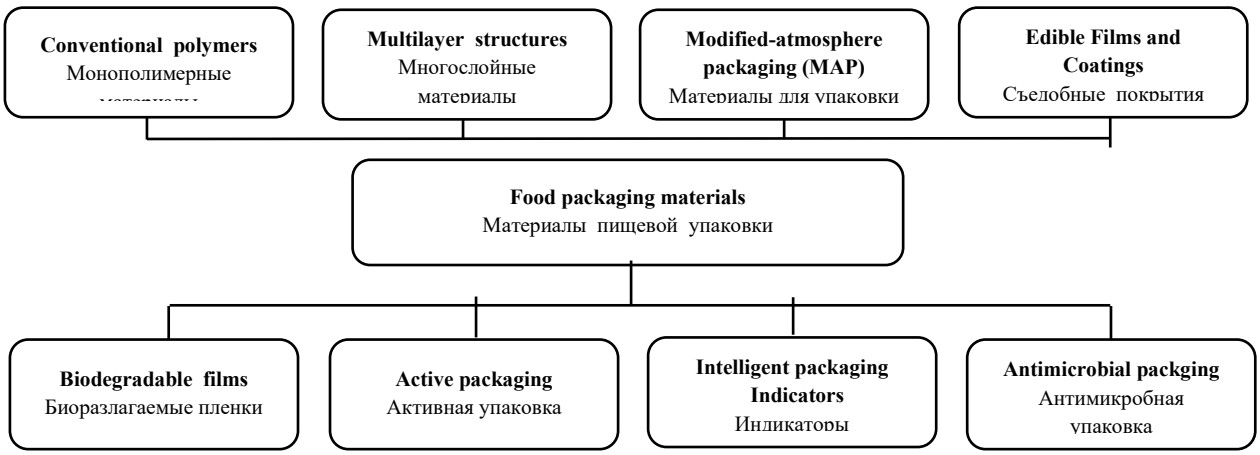


Figure 2. Main groups of materials used in food packaging

Table 1.

Comparative Characteristics of Major Classes of Food Packaging Materials

Материал / Material	Основная функция / Main function	Преимущества / Advantages	Ограничения / Limitations
Монополимерные материалы/ Conventional polymers	Барьерная и механическая защита / Barrier and mechanical protection	Низкая стоимость, высокая технологичность / Low cost, high processability	Пластиковые отходы, миграция добавок / Plastic waste and additive migration
Многослойные материалы/ Multilayer structures	Комбинированный газо и влагозащитный барьер / Combined gas and moisture barrier	Высокая защита чувствительных продуктов / Strong protection for sensitive foods	Сложность переработки / Difficult recycling
Биоразлагаемые пленки / Biodegradable films	Снижение зависимости от нефтехимических полимеров / Lower dependence on petrochemical polymers	Экологический потенциал / Environmental potential	Слабый влагобарьер и более высокая стоимость / Weak moisture barrier and higher cost
Активная и интеллектуальная упаковка / Active and intelligent packaging	Поглощение, высвобождение или индикация / Scavenging, release or indication	Контроль окисления, влаги и свежести / Oxidation, moisture and freshness control	Миграция, валидация и регуляторные требования / Migration, validation and regulatory burden
Съедобные пленки и покрытия / Edible films and coatings	Защита поверхности и доставка биоактивных соединений / Surface protection and delivery of bioactive compounds	Снижение отходов упаковки и повышение качества продукции / Reduced packaging waste and improved product quality	Ограниченная механическая прочность и влагостойкость / Limited mechanical strength and moisture resistance
Антимикробная / Antimicrobial	Ингибирование роста микроорганизмо/Inhibition of microbial growth	Снижение микробной порчи и продление срока годности/ Reduced microbial spoilage and extended shelf life	Контролируемое высвобождение, сенсорное влияние миграционная безопасность /Controlled release, sensory impact and migration safety

Примечание. Представленная классификация носит обобщенный характер и может изменяться в зависимости от состава материала, технологии производства и области применения.
Note. The presented classification is generalized and may vary depending on material composition, processing technology and intended food application.

Food-packaging materials can be examined through two complementary perspectives: chemical structure and preservation function. Conventional polymers, including polyethylene, polypropylene, polyethylene terephthalate, and polyamide, continue to dominate industrial practice because they combine acceptable barrier properties, mechanical durability, and economical processing. their principal limitation is not an immediate lack of technological usefulness but the environmental burden, recycling complexity, and possible additive migration associated with large-scale use [2, 14–17].

Multilayer structures compensate for the weaknesses of individual polymers by distributing functions across separate layers, including sealability, puncture resistance, water-vapor control, oxygen protection, and light protection. This architecture is valuable for meat, dairy products, ready meals, and other oxidation-sensitive or moisture-sensitive foods. the drawback appears at the end of the package life cycle: chemically incompatible layers are difficult to separate and frequently remain unsuitable for conventional mechanical recycling [13, 16, 17].

Edible, biodegradable, active, intelligent, and antimicrobial systems respond to requirements that conventional plastics address only partially. Edible coatings may limit surface moisture loss and act as carriers for antioxidant or antimicrobial compounds. biodegradable films based on starch, cellulose, chitosan, polylactic acid, or polyhydroxyalkanoates reduce reliance on fossil resources, although their mechanical strength and barrier performance often require blending or surface coating [3–6, 18–20]. active packaging is designed to absorb oxygen, regulate moisture, or release protective substances; antimicrobial packaging specifically aims to inhibit or delay the growth of bacteria, yeasts, and molds on the product surface or in the package headspace. such effects may be achieved through organic acids, enzymes, chitosan, bacteriocins, plant extracts, essential oils, or other approved antimicrobial agents incorporated into films, coatings, sachets, or surface layers.

Intelligent indicators register ph shifts, temperature abuse, or volatile-spoilage markers without necessarily exerting a preservative effect [7–11, 21, 24].

Factors Determining Packaging Performance

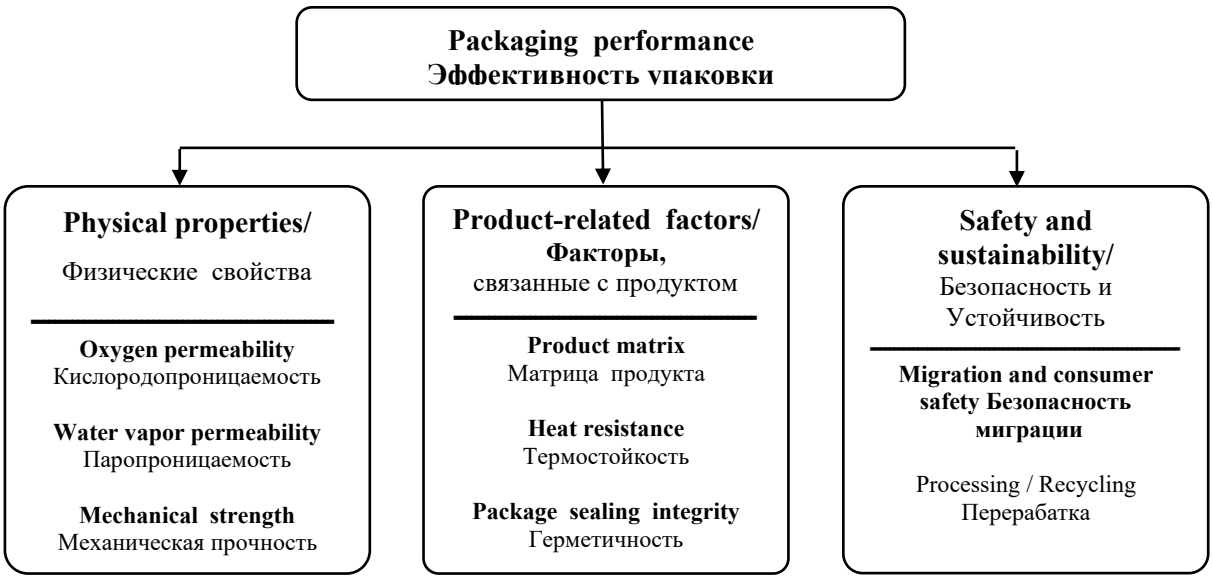


Figure 3. Factors determining the performance of food packaging

Packaging efficiency is best treated as a system-level property. Oxygen transmission rate, water-vapor transmission rate, film thickness, seal integrity, puncture resistance, headspace composition, light exposure, microbial load, and storage temperature become meaningful only when they are considered in relation to the food matrix. A lipid-rich product, a respiring vegetable, and a high-moisture chilled meal require different barrier and antimicrobial profiles. A film that prevents dehydration in meat or cheese may, under another set of conditions, promote condensation and increase microbial risk in fresh produce.

Food-contact safety must be assessed alongside preservation performance. Packaging materials may contain intentionally added substances, residual monomers, additives, processing aids, and non-intentionally added substances. In antimicrobial packaging, additional attention is required because active compounds may be released deliberately or may

migrate from the contact layer into the food. The acceptability of such systems depends on migration limits, toxicological evaluation, sensory neutrality, target-microorganism specificity, and predictable release kinetics. Accordingly, sustainable packaging cannot be judged solely by biodegradability or recyclability claims; it must also be microbiologically effective, safe in food contact, compatible with the product matrix, and realistic in its end-of-life route [10, 11, 14–17].

Practical Limitations and Risk-Benefit Balance

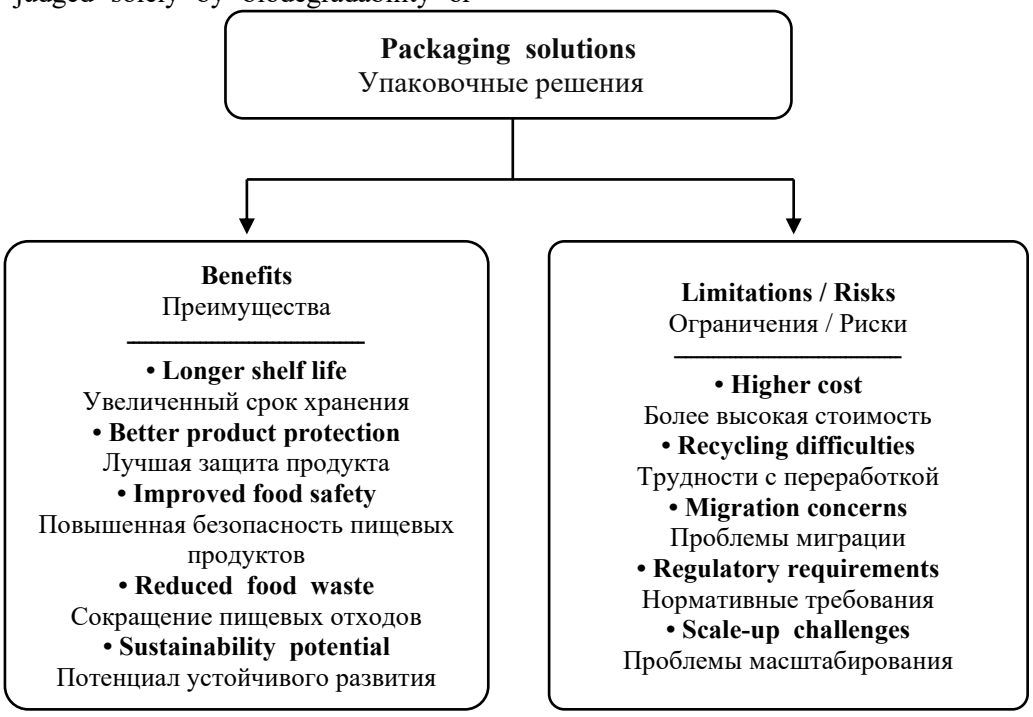


Figure 4. Risk–benefit balance of modern food packaging solutions

Each packaging option involves a compromise between technological benefit and practical burden. Conventional polymers offer low cost and robust processability, but their environmental footprint and chemical complexity remain substantial. Multilayer films provide strong protection for sensitive products, although they are among the most difficult flexible materials to recycle. Biodegradable films may reduce dependence on petrochemical polymers; however, many lose strength or barrier performance at high relative humidity and may require industrial composting conditions that are not widely available [18–20].

Active and intelligent systems are valuable because they extend packaging beyond passive containment. Their industrial use, nevertheless, depends on predictable release kinetics, reliable indicator response, food-specific calibration, and regulatory acceptance. Nanocomposites may improve barrier and antimicrobial performance, but toxicological data and migration behavior must be established before broad food-contact application. In practice, the most appropriate option is rarely the newest material; it is the system in which benefits and risks are proportionate to the product, the intended shelf life, and the supply chain [7–11, 21, 24, 25].

Industrial Packaging Methods and Application Areas

Packaging methods should be selected according to product characteristics rather than equipment availability alone. Form-fill-seal systems are efficient for dry and granular foods. Vacuum packaging and vacuum skin packaging reduce oxygen exposure and improve the presentation of meat, fish, cheese, and nuts, although they may deform fragile products. Modified-atmosphere packaging offers greater flexibility because the gas composition can be adjusted to the product, but its effectiveness depends on seal integrity, film permeability, initial microbial load, and cold-chain control.

Aseptic filling and hot filling are most appropriate for liquid or semi-liquid products where microbial safety must be secured before or during filling. Retort processing remains essential for shelf-stable low-acid foods, although intensive heat treatment can impair sensory and nutritional quality. High-pressure processing requires flexible or semi-flexible packaging that can withstand compression without seal failure or marked changes in permeability, Edible and antimicrobial coatings may be useful for fruit, vegetables, cheese, and selected meat

products when adhesion, drying conditions, release behavior, antimicrobial efficacy, and sensory acceptability are adequately controlled [22–27].

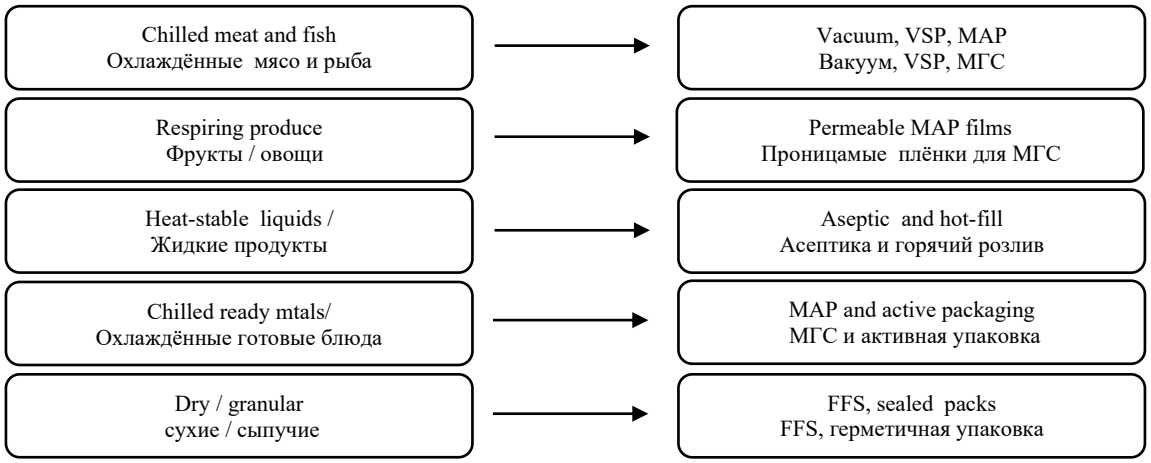


Figure 5. Logic for selecting a packaging system according to product profile

Table 2.

Main packaging methods and preferred application areas

Метод / Method	Оборудование / Equipment	Подходящие продукты / Suitable products	Ключевое преимущество / Key benefit
Формовочно-фасовочная упаковка (FFS) / Form-fill-seal (FFS)	Вертикальные или горизонтальные автоматы / Vertical or horizontal machines	Сухие и сыпучие продукты / Dry and granular foods	Высокая производительность / High throughput
Вакуум, VSP, МГС / Vacuum, VSP, MAP	Вакуумные камеры, газовые смесители / Vacuum chambers, gas mixers	Мясо, рыба, сыр, охлажденные продукты / Meat, fish, cheese, chilled foods	Снижение окисления и порчи / Reduced oxidation and spoilage
Асептический и горячий розлив / Aseptic and hot filling	Теплообменники, стерильные наполнители / Heat exchangers, sterile fillers	Молоко, соки, соусы / Milk, juices, sauces	Стабильность при хранении / Storage stability
Ретортная обработка и HPP / Retort processing and HPP	Автоклавы, камеры высокого давления / Retorts, pressure vessels	Низкокислотные блюда, охлажденные продукты / Low-acid meals, chilled foods	Безопасность и длительный срок годности / Safety and shelf life

Примечание. Способ упаковки выбирается исходя из состава продукта, активности воды, чувствительности к кислороду, необходимого срока годности, температурного режима и логистических условий. Приведенные области применения являются обобщенными и могут быть уточнены в соответствии с технологическими требованиями конкретного продукта.
Note. The packaging method is selected based on the product composition, water activity, oxygen sensitivity, shelf life needed, temperature regime, and logistics conditions. The application areas shown are generalized and can be refined according to the technological requirements of a specific product.

Development Prospects

Research is increasingly directed toward packaging systems that combine environmental responsibility with active or diagnostic functionality. Studies on sustainable materials now give particular attention to recyclable mono-materials, biodegradable films strengthened by blending, and polymers or coatings derived from agricultural and food-processing byproducts [20, 28]. In parallel, antimicrobial packaging has become an important direction within active packaging. systems containing chitosan, bacteriocins, enzymes, organic acids, plant extracts, essential oils, oxygen scavengers, or controlledrelease structures are being developed to slow oxidation and microbial spoilage, especially in high-moisture, protein-rich, and lipid-rich foods [7, 10, 11, 21].

Intelligent packaging is increasingly linked with digital traceability. Time-temperature indicators, pH-sensitive labels, volatile-amine indicators, QR codes, RFID systems, and blockchain-based records may help replace fixed expiration dates with more accurate information about product history and remaining shelf life [9, 24, 29, 30]. Non-thermal technologies, including high-pressure processing and cold plasma, extend this direction by enabling preservation after packaging or with reduced heat damage; nevertheless, packging compatibility, migration behavior, antimicrobial stability, and

posttreatment microbial control still require verification [10, 11, 27, 30].

Conclusion

Food packaging should be regarded as an integrated preservation system rather than a single material layer. Conventional polymers, multilayer films, biodegradable films, active systems, intelligent indicators, and antimicrobial materials all have justified fields of application, but none can be considered universal. Effective design requires simultaneous evaluation of product sensitivity, barrier performance, seal integrity, processing method, microbial risk, migration safety, cost, storage conditions, and end-of-life management.

Future progress is likely to depend on product-specific multifunctional systems. Such systems should extend shelf life while protecting consumer safety, preserving sensory and nutritional quality, reducing waste, supporting traceability, and remaining economically feasible at industrial scale. the central challenge is therefore not simply to replace conventional plastics, but to select and engineer packaging systems whose technical, microbiological, safety, and environmental performance are balanced for a defined food product and supply chain.

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Contribution

All authors are equally involved in the writing of the manuscript and are responsible for plagiarism

Conflict of interest

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Упаковочные решения для пищевых продуктов, методы применения, ограничения и будущий потенциал

Аннотация. Цель обзора состояла в анализе современных технологий упаковочных решений для продуктов питания и определении факторов, которые необходимо учитывать при выборе упаковочной системы для конкретного продукта. Работа выполнена как структурированный нарративный обзор с четко заданной стратегией литературного поиска. Проанализированы рецензируемые публикации, индексируемые в Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley и Google Scholar, преимущественно за 2018–2026 гг., с приоритетом источников, имеющих DOI и прямое отношение к материалам, контактирующим с пищевой продукцией. В статье рассмотрены как, традиционные монополимерные и многослойные материалы, материалы для упаковки в модифицированной газовой среды, съедобные и биоразлагаемые покрытия, активные и интеллектуальные упаковочные системы, а также антимикробные материалы. Установлено, что эффективность упаковки определяется не отдельным барьерным показателем, а совокупностью свойств: кислородо- и паропроницаемостью, прочностью сварного шва, матрицей продукта, миграционной безопасностью и возможностью переработки. Обобщены области применения формовочно-фасовочных систем, вакуумной упаковки, упаковки в модифицированной газовой среде, асептического и горячего розлива, ретортной обработки, съедобных покрытий и упаковки, совместимой с обработкой высоким давлением. Показано, что наиболее перспективны многофункциональные решения, объединяющие устойчивые материалы, активную защиту, индикаторный контроль, цифровую прослеживаемость и совместимость с нетермическими технологиями. Практическая значимость работы состоит в формировании критериев для предварительного выбора упаковки на этапах разработки продукта, технологического проектирования и оценки рисков. Результаты обзора могут быть использованы при проектировании упаковки для мясных, рыбных, молочных, растительных и готовых пищевых продуктов.

Ключевые слова: упаковочные решения, биоразлагаемые материалы, активная упаковка, интеллектуальная упаковка, модифицированная газовая среда, безопасность миграции, устойчивость.

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