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APPLICATION OF MOLECULAR HYDROGEN IN FOOD PRODUCTION AND PRESERVATION: CURRENT TRENDS AND FUTURE PROSPECTS (REVIEW)

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The modern food industry faces many challenges, including accelerated processes of oxidative degradation of lipids and proteins, active reproduction of pathogenic microflora, limited shelf life and accumulation of toxic compounds, which necessitates the introduction of innovative and environmentally friendly technologies to ensure the quality and safety of products. In this context, molecular hydrogen (H_2) is considered a promising functional agent due to its high diffusion capacity and selective antioxidant activity, which allows it to effectively neutralize the most reactive radicals without interfering with natural biochemical processes. Studies show that the use of H_2 in the meat and dairy industries helps to slow down peroxidation processes, preserve nutritional value and organoleptic characteristics, reduce the formation of biogenic amines and inhibit the development of microbial flora, and its role in storage and freezing technologies is expressed in stabilizing tissue structures, preventing darkening of vegetables and fruits and reducing vitamin losses. The use of hydrogen in modified gas environments and biopolymer coatings opens up new opportunities for extending shelf life and increasing microbiological safety, while integration into plant-based raw material processing and beverage production processes helps preserve antioxidant potential, optimize fermentation, and reduce the formation of undesirable by-products. The totality of the data obtained confirms that molecular hydrogen is an environmentally friendly and effective tool for the sustainable development of food technologies.

Keywords: molecular hydrogen, food preservation, antioxidant activity, antimicrobial properties, biogenic amines, meat and dairy products, hydrogen-rich water (HRW), food safety.

ТАМАҚ ӨНІМДЕРІН ӨНДІРУДЕ ЖӘНЕ САҚТАУДА МОЛЕКУЛАЛЫҚ СУТЕКТІ ҚОЛДАНУ: ҚАЗІРГІ ЗАМАНҒЫ ҮРДІСТЕР МЕН ПЕРСПЕКТИВАЛАР (ШОЛУ)

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Қазіргі заманғы тамақ өнеркәсібі липидтер мен ақуыздардың тотығу тозуының жеделдетілген процестерін, патогенді микрофлораның белсенді көбеюін, сақтау мерзімінің шектелуін және уытты қосылыстардың жинақталуын қоса алғанда, көптеген сын-қатерлерге тап болады, бұл өнімнің сапасы мен қауіпсіздігін қамтамасыз ету үшін инновациялық және экологиялық таза технологияларды енгізу қажеттілігін негіздейді. Бұл контексте молекулалық сутек (H_2) өзінің жоғары диффузиялық қабілеті мен селективті антиоксиданттық белсенділігінің арқасында перспективалы функционалдық агент болып саналады, бұл оған табиғи биохимиялық процестерге араласпай, ең реакцияға қабілетті радикалдарды тиімді бейтараптандыруға мүмкіндік береді. Зерттеулер H_2 ет және сүт өнеркәсібінде пайдалану тотығу процестерін баяулатуға, қоректік құндылығы мен органолептикалық сипаттамаларын сақтауға, биогендік аминдердің пайда болуын азайтуға және микробтық флораның дамуын тежеуге көмектесетінін және оның сақтау және мұздату технологияларындағы рөлі тіндердің құрылымын тұрақтандырудан, көкөністер мен жемістердің қараңғылануын болдырмаудан және ысырапты азайтудан көрінеді дәрумендер. Түрлендірілген газ ортасы мен биополимерлік жабындарда сутекті пайдалану жарамдылық мерзімін ұзарту және микробиологиялық қауіпсіздікті арттыру үшін жаңа мүмкіндіктер ашады, ал өсімдік шикізатын қайта өңдеу және сусындарды өндіру процестеріне интеграциялау антиоксиданттық әлеуетті сақтауға, ферменттеуді оңтайландыруға және жағымсыз жанама өнімдердің пайда болуын азайтуға көмектеседі. Алынған деректердің жиынтығы молекулярлық сутегі тамақ технологияларын тұрақты дамытудың экологиялық таза және тиімді құралы болып табылатынын растайды.

Түйін сөздер: молекулалық сутек, тамақ өнімдерін консервациялау, антиоксиданттық белсенділік, микробқа қарсы қасиеттер, биогендік аминдер, ет және сүт өнімдері, сутегіге байытылған су (HRW), тамақ өнімдерінің қауіпсіздігі

ПРИМЕНЕНИЕ МОЛЕКУЛЯРНОГО ВОДОРОДА В ПРОИЗВОДСТВЕ И СОХРАНЕНИИ ПРОДУКТОВ ПИТАНИЯ: СОВРЕМЕННЫЕ ТЕНДЕНЦИИ И ПЕРСПЕКТИВЫ (ОБЗОР)

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Современная пищевая промышленность сталкивается со многими вызовами, включая ускоренные процессы окислительной деградации липидов и белков, активное размножение патогенной микрофлоры, ограниченный срок хранения и накопление токсичных соединений, что обуславливает необходимость внедрения инновационных и экологически чистых технологий для обеспечения качества и безопасности продукции. В этом контексте молекулярный водород (H_2) считается перспективным функциональным агентом благодаря своей высокой диффузионной способности и селективной антиоксидантной активности, что позволяет ему эффективно нейтрализовать наиболее реакционноспособные радикалы, не вмешиваясь в естественные биохимические процессы. Исследования показывают, что использование H_2 в мясной и молочной промышленности помогает замедлить процессы перекисного окисления, сохраняют питательную ценность и органолептические характеристики, уменьшают образование биогенных аминов и тормозят развитие микробной флоры, и его роль в технологиях хранения и замораживания выражается в стабилизации структур тканей, предотвращение потемнения овощей и фруктов и снижение потерь витаминов. Использование водорода в модифицированных газовых средах и биополимерных покрытиях открывает новые возможности для продления срока годности и повышения микробиологической безопасности, а интеграция в процессы переработки растительного сырья и производства напитков помогает сохранить антиоксидантный потенциал, оптимизировать ферментацию и уменьшить образование нежелательных побочных продуктов. Совокупность полученных данных подтверждает, что молекулярный водород является экологически чистым и эффективным инструментом устойчивого развития пищевых технологий.

Ключевые слова: молекулярный водород, консервация пищевых продуктов, антиоксидантная активность, антимикробные свойства, биогенные амины, мясные и молочные продукты, вода обогащенная водородом (HRW), безопасность пищевых продуктов.

Introduction. Modern food production faces many challenges that directly affect their quality and safety: accelerated oxidation of fats and proteins, growth of pathogenic microflora, reduction of shelf life and formation of toxic compounds. All this prompts the search for new, effective and environmentally friendly preservation methods. In this context, molecular hydrogen (H_2) is considered as an extremely promising tool that can extend shelf life, stabilize food matrices and improve food safety [1]. Research interest in the use of H_2 in food technology is due to its physicochemical properties - small molecule size and high diffusion capacity, which ensures free penetration through cell membranes and uniform distribution in tissues, which allows hydrogen to interfere with the oxidation-reduction balance and prevent deterioration of the organoleptic and nutritional characteristics of food [2]. One of the key features of hydrogen application is its antioxidant activity. It is highly selective: it effectively neutralizes only the most reactive and toxic radicals, such as •OH (hydroxyl radical) and ONOO (peroxynitrite), without affecting normal cellular signaling and metabolic processes [3].

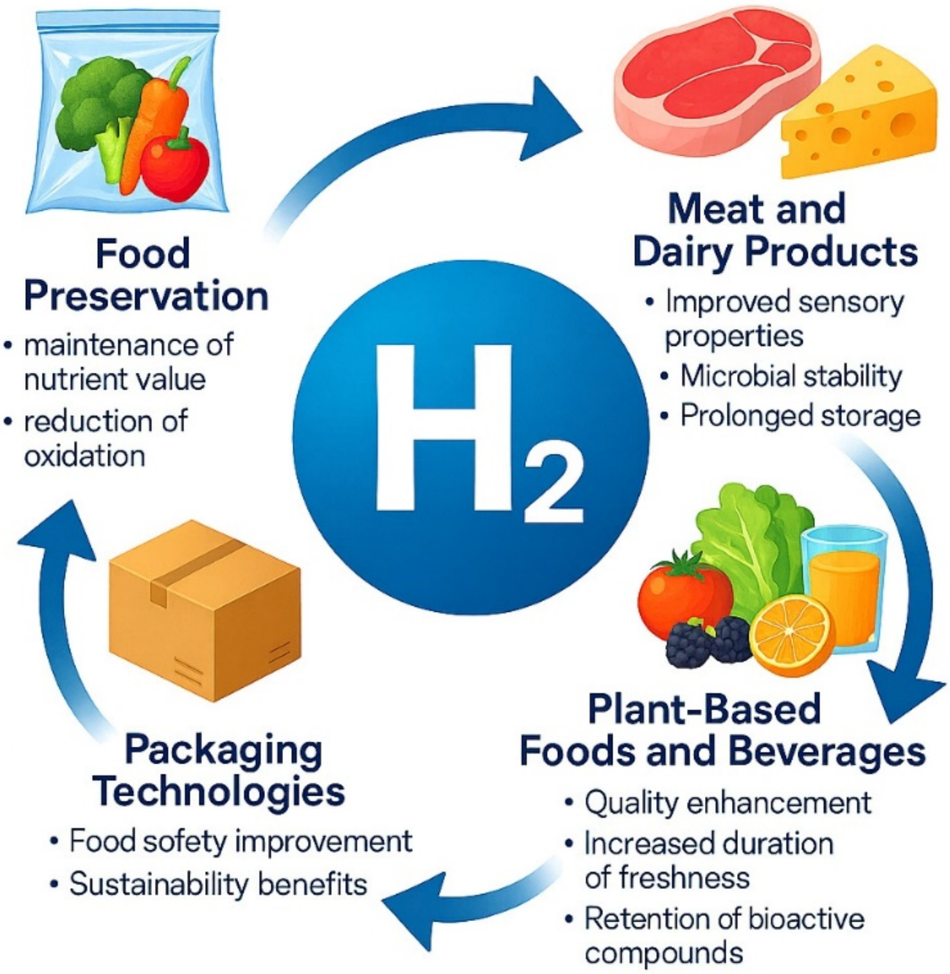

Fig.1 – Applications of Molecular Hydrogen in Food Production and Preservation

In the meat industry, saturation of products with molecular hydrogen or the use of hydrogen-containing films helps reduce lipid and protein peroxidation, slow down the growth of microbial flora and increase product freshness. In the dairy and fat industry, H_2 helps preserve organoleptic properties and prevent rancidity, which is confirmed by studies using butter and margarines as an example [4].

Food packaging plays a vital role in food industry by maintaining product quality, extending shelf life and ensuring food safety. However, conventional food packaging systems are limited in their ability to inhibit bacterial growth, prevent oxidative spoilage, and preserve product freshness [5,6]. The use of H_2 in packaging and storage technologies is also promising. The introduction of molecular hydrogen into modified gas environments and the development of hydrogen-containing biopolymer films enhance the barrier properties of packaging, reducing oxidation and microbial contamination, thereby increasing the shelf life and safety of products [7].

Another important area is the reduction of the formation of biogenic amines and carcinogenic compounds.

For example, saturation of meat raw materials with hydrogen reduces the accumulation of histamine, tyramine and other biogenic amines - markers of microbiological spoilage and potential danger to humans. In addition, the use of hydrogen as a fuel when frying meat reduces the formation of polycyclic aromatic hydrocarbons and volatile organic compounds, reducing the carcinogenic load [8].

The topic is actively developing at the international level: in Japan, South Korea and China, fundamental and applied research is being conducted on the implementation of hydrogen technologies in food production, while in Europe and the USA, attention is focused on the safety and technological integration of H_2 into existing lines [9]. Thus, the existing studies allow us to consider molecular hydrogen as a promising technological factor that simultaneously ensures an increase in shelf life, microbiological safety and preservation of the sensory properties of products. Generalization and in-depth analysis of the areas of application of H_2 in the food industry is an important task of modern science [10].

The objective of this review is to assess the existing and recent advances in the use of molecular hydrogen in food production and safety, provide a summary of the main research directions, and determine the feasibility of its practical implementation in the food production industry.

1. *Antioxidant properties of molecular hydrogen*

The problem of oxidative processes in food is fundamental: they are the ones that cause loss of freshness, formation of rancid taste, darkening of color, appearance of foreign odors and destruction of nutrients. The most vulnerable are fats and proteins, which undergo peroxidation, resulting in the formation of toxic by-products. These reactions not only reduce shelf life, but also directly affect the safety of finished products. Therefore, the search for new antioxidant solutions that could be both effective and safe remains one of the priority tasks of modern nutrition science [11].

Antioxidant properties of molecular hydrogen (H_2) are now considered one of the key factors determining the prospects of its use in the food industry. The key feature of molecular hydrogen is its selective antioxidant activity. Unlike vitamins (ascorbic acid, tocopherols) or synthetic antioxidants (butylhydroxyanisole, butylhydroxytoluene), which act non-specifically and can interfere with beneficial metabolic processes, H_2 reacts exclusively with the most aggressive radicals. These include the hydroxyl radical (•OH) and peroxynitrite (ONOO) - highly reactive molecules that damage lipids, proteins, nucleic acids and initiate avalanche-like chain reactions of oxidation. At the same time, H_2 does not affect the superoxide anion or hydrogen peroxide, which perform important physiological functions, such as participation in cellular signaling. This selectivity distinguishes hydrogen favorably from all known antioxidants and makes it extremely attractive for applied use [12].

The use of H2 in food technology has demonstrated its effectiveness in a wide range of products. For example, in the meat industry, hydrogen treatment of raw materials reduced the level of malondialdehyde, a marker of lipid peroxidation, thereby preserving the taste and smell of products for longer. In the dairy industry, saturation of butter with hydrogen prevented rancidity, slowed down texture changes, and preserved the characteristic aroma. In studies with grain products, it was shown that treatment of rice with hydrogen nanobubble water improved storage, reduced the accumulation of volatile substances, and prevented the formation of unpleasant odors. In vegetables and fruits, the use of H2 allowed the preservation of bright color, reduced darkening, and preserved the content of vitamins C and E, which are usually quickly destroyed by oxygen [4].

The antioxidant properties of molecular hydrogen also have a pronounced sanitary and hygienic significance. Lipid oxidation products, such as aldehydes and ketones, can accumulate in the body and provoke the development of inflammatory processes and chronic diseases. For the food industry, this is not only a quality problem, but also an important safety issue: products with high concentrations of secondary oxidation products are potentially dangerous for consumers. The use of H_2 can significantly reduce the level of these compounds in finished products, minimizing health risks and increasing confidence in products on the market [7].

An important area of research is the study of the stability of the antioxidant effect of H_2 in various matrices. It has been shown that in fat systems (oils, margarines), H_2 effectively prevents rancidity and preserves the texture of the product, and in protein systems (meat, dairy products), it inhibits the formation of carbon derivatives and increases resistance to microbiological spoilage. In beverages, especially functional ones (juices, energy and sports drinks), the use of hydrogen-rich water (HRW) has shown high efficiency in preserving the antioxidant potential and prolonging shelf life. These data expand the boundaries of hydrogen application and make it a universal tool for different segments of the food industry [8].

The complex of antioxidant properties of molecular hydrogen covers various levels of protection of food matrices: it prevents rancidity of lipid components, stabilizes the color and texture characteristics of protein structures and thereby maintains the organoleptic quality of products [13]. Considering H_2 as an innovative preservative, we can talk about its potential to partially replace or supplement existing antioxidant systems. In the future, this will contribute to the gradual rejection of excessive use of synthetic additives and the formation of ”clean” and environmentally sustainable food production technologies.

2. *Antimicrobial action of molecular hydrogen*

Microbiological safety of food products remains one of the most pressing issues in the food industry, since it is the growth of pathogenic and opportunistic microflora that is the main reason for the reduction of shelf life, changes in organoleptic characteristics and the emergence of risks to human health [14]. The presence of microorganisms such as Salmonella spp., Listeria monocytogenes, Escherichia coli O157:H7 and Staphylococcus aureus leads to serious product losses and threatens the epidemiological situation. Traditional control methods are based on heat treatment, the addition of preservatives or the use of a modified gas environment, but their effectiveness is limited: heating destroys nutrients and vitamins, chemical additives reduce the environmental friendliness of the product and raise safety concerns, and gas mixtures do not always prevent the development of resistant forms of microorganisms. Against this background, molecular hydrogen (H_2) has emerged as a promising agent capable of providing an antimicrobial effect without negative consequences for food quality [15].

The antimicrobial effect of hydrogen is not associated with direct cell destruction, but with the regulation of the redox balance and a decrease in the level of oxidative stress in the environment. This leads to the suppression of the activity of membrane enzymes of microorganisms and the inhibition of cell division processes. Unlike antibiotics or traditional preservatives, H_2 does not disrupt beneficial microbiota and does not cause the formation of resistant strains, which makes its use safer and more environmentally friendly [16]. Experiments have shown that the use of hydrogen during the storage of meat products slows the growth of psychrotrophic bacteria and allows to extend their shelf life by several days. In addition, hydrogen reduces the formation of biogenic amines, such as histamine, tyramine and cadaverine, which are formed during the microbiological decomposition of proteins and can cause serious poisoning in humans [4].

Positive results have also been recorded in the dairy industry: saturation of dairy products with hydrogen inhibits the rapid development of acid-forming bacteria, which prevents premature fermentation and souring. When processing butter and margarines, hydrogen suppressed the growth of microorganisms and thereby slowed down the spoilage process, preserving the aroma and consistency of fatty products longer than the standard shelf life [8]. In seafood, treatment with hydrogen water reduced the rate of formation of amines and sulfur compounds, which are the result of protein degradation and determine the characteristic smell of spoilage. Similar effects were observed in the processing of vegetables and fruits, where hydrogen reduced the development of fungal microflora, helped to preserve the appearance of the fruit and prevented darkening of the surface [17].

An additional significance of the antimicrobial action of H2 is the reduction of the toxicological load of products. When hydrogen was used as a fuel in the heat treatment of meat, a reduction in the formation of polycyclic aromatic hydrocarbons and volatile organic compounds with carcinogenic properties was recorded [9]. Thus, hydrogen not only inhibits the growth of microorganisms, but also reduces the formation of hazardous chemical compounds, which makes it especially valuable for comprehensive safety.

The totality of available data allows us to conclude that molecular hydrogen is an effective factor capable of significantly increasing the microbiological safety of food products. It simultaneously slows down the growth of pathogenic microflora, prevents the formation of toxic metabolites and helps preserve the freshness and quality of products. These properties make H_2 a promising tool for the development of new storage and processing technologies focused on sustainability, environmental friendliness and consumer health protection [10].

3. *Use of hydrogen in the meat and dairy industries*

The meat and dairy industries are traditionally considered the most vulnerable segments of the food industry, as their products are prone to rapid oxidation and microbiological spoilage. The high content of proteins, lipids and moisture creates a favorable environment for the development of pathogenic flora and also accelerates oxidation processes. This is why meat, sausages, milk and dairy products have a limited shelf life and require the use of preservation technologies. Traditional methods include heat treatment, pasteurization, vacuum packaging and the use of preservatives, but they do not always ensure the preservation of organoleptic properties and often lead to the destruction of valuable nutrients. Against this background, molecular hydrogen (H_2) is considered an innovative and environmentally friendly tool that can provide comprehensive protection against oxidative and microbiological changes without compromising product quality [4].

The use of H2 in the meat industry demonstrates a number of positive effects. One of the main ones is the suppression of lipid peroxidation, which is the cause of rancidity and the formation of an unpleasant odor. Studies have shown that saturating meat raw materials with hydrogen or storing it in an atmosphere containing H2 reduces the level of malondialdehyde, a marker of lipid peroxidation, and slows down the formation of secondary oxidation products. As a result, meat retains its fresh color, characteristic taste, and elastic texture longer. In addition, H2 treatment prevents the destruction of proteins and amino acids, which helps preserve the nutritional value of the product. It is especially important that the effect is achieved without changing the organoleptic profile and without the need to use synthetic antioxidants such as butylhydroxyanisole or butylhydroxytoluene, the use of which is restricted by law [8].

Of additional importance is the effect of H2 on the microbiological stability of meat products. Experiments have shown that treating chilled meat with a hydrogen environment slows the growth of psychrotrophic bacteria, which increases the shelf life by 2-3 days. In sausages, the introduction of hydrogen reduced the formation of biogenic amines - histamine, tyramine, and cadaverine - which are formed during the microbial decomposition of proteins. These compounds not only worsen organoleptic characteristics, but also pose a serious risk to human health, causing allergic reactions and food poisoning. Thus, hydrogen ensures both sensory and sanitary-hygienic stability of meat products [4].

No less impressive results have been obtained in the dairy industry. Butter and margarine are particularly susceptible to rancidity due to the high concentration of unsaturated fatty acids, which are easily oxidized. Saturation of such products with H_2 significantly slows down their spoilage, prevents the formation of an unpleasant odor and bitter taste, and also maintains a soft consistency. In milk, hydrogen reduces the activity of acid-forming bacteria, which prevents rapid souring and extends shelf life without the use of antibiotics or preservatives. Moreover, experiments have shown that hydrogen treatment prevents the destruction of vitamins A and E, which are usually lost as a result of oxidative processes, which increases the nutritional value of dairy products [9].

The possibility of using H2 in modified gas mixtures for food packaging attracts particular attention from researchers. The introduction of hydrogen into the gas composition together with carbon dioxide and nitrogen provides an additional level of protection against oxidative processes and microbial contamination. This approach allows for simultaneously extending the shelf life and preserving the organoleptic qualities of meat and dairy products. Moreover, the development of active packaging technologies using hydrogen-containing biopolymer films opens up new prospects: such materials not only create a barrier for oxygen and microorganisms but also act as an active preservative [10].

An interesting area is the use of hydrogen as a fuel in the thermal processing of meat products. It has been shown that the use of hydrogen for frying meat reduces the formation of polycyclic aromatic hydrocarbons (PAH) and volatile organic compounds with carcinogenic properties. At the same time, the product retains its usual sensory characteristics, such as taste and aroma. This makes the technology especially valuable for meat processing plants seeking to improve product safety and reduce health risks for consumers [8].

Taken together, the results of numerous studies confirm that molecular hydrogen is an effective tool for extending shelf life and improving the quality of meat and dairy products. Its use allows for the simultaneous solution of problems of antioxidant protection, microbiological stability and toxicological safety. Unlike traditional methods, H_2 provides a comprehensive effect and is environmentally safe, which makes its implementation particularly relevant in the context of the global trend towards “clean label” and sustainable production technologies [9].

4. *Use of Hydrogen in Freezing and Storage Technologies*

Freezing and refrigerated storage are basic methods of preserving food products, but their effectiveness is limited by a number of serious problems [18]. At low temperatures, the oxidation of fats and proteins slows down, but does not stop completely, which leads to a gradual deterioration in organoleptic characteristics. Meat and fish darken, lose elasticity and aroma, dairy products acquire a rancid taste, vegetables and fruits lose color and freshness. An additional problem is the formation of ice crystals in tissues: when frozen, they damage cell membranes, disrupt water-holding capacity and worsen the texture of products after defrosting. These changes not only reduce consumer properties, but also increase the volume of food waste. Against this background, molecular hydrogen (H_2) is increasingly considered as an innovative factor that can improve storage efficiency and minimize damage that occurs during the freezing process [4].

The use of H_2 in storage technologies has demonstrated high efficiency in the meat and fish industries. Studies have shown that saturation of meat raw materials with hydrogen before freezing reduces the intensity of lipid peroxidation, which helps preserve the natural color and aroma of the meat. Similar results were obtained in the storage of seafood. Experiments with dried shrimp showed that the use of a modified atmosphere with H_2 effectively slows down quality deterioration during accelerated storage, extending shelf life without the use of synthetic preservatives. At the same time, the products retained their characteristic taste and texture, which is especially important for premium products aimed at export [19].

The effectiveness of hydrogen has also been confirmed in the storage of plant products. Fruits and vegetables are very sensitive to oxidative processes and enzymatic darkening, which is associated with the activity of polyphenol oxidase. When processing strawberries with a hydrogen-containing packaging atmosphere, it was possible to significantly slow down the loss of vitamins, prevent darkening, and preserve the fresh aroma of the berries throughout the entire storage period. Such results demonstrate the potential of H_2 as an environmentally friendly tool for the transportation and sale of perishable plant products [20].

Additional studies on fresh-cut fruits showed that hydrogen can protect products even under conditions of high tissue metabolism. Thus, when storing apples in an atmosphere with H_2, there was a slowdown in browning, an improvement in texture, and the preservation of antioxidant activity. Hydrogen not only extended the shelf life, but also preserved the functional properties of the product, making it more useful for consumers. These results are especially important for the fresh-cut sector, where the shelf life is usually limited to a few days [21].

The use of H_2 in the dairy industry has also yielded convincing results. In experiments with butter and margarine, it was shown that hydrogen saturation slows the rate of rancidity, reduces the accumulation of biogenic amines, and allows for an extension of shelf life to 30 days without changing sensory characteristics. The products retained a soft consistency and natural taste, making H_2 an effective tool for increasing the stability of fatty products. In fresh milk and fermented milk drinks, H_2 slowed the development of acid-forming bacteria, prevented premature souring, and increased stability during storage under refrigerated conditions [22].

Particular attention is paid to the combined use of H_2 with modern methods of active packaging. Hydrogen can be included in modified gas mixtures (MAP), together with nitrogen and carbon dioxide, providing multi-level protection: from oxidative processes, microbial contamination and enzymatic changes. Experiments have shown that MAP with H_2 allows preserving the freshness of vegetables, fruits and seafood much longer than traditional gas mixtures. In addition, the development of hydrogen-containing biopolymer films opens up new possibilities in the field of ”smart packaging”, where the material not only isolates the product from the external environment, but also actively maintains its quality during storage [23].

The body of evidence suggests that hydrogen could become a key factor in storage and freezing technologies. It reduces the rate of oxidation processes, stabilizes tissue structure, prolongs freshness and increases product safety. In the future, hydrogen storage technologies could play an important role in the sustainable development strategy of the food industry, reducing food losses and minimizing the use of chemical additives.

5. *Hydrogen and Packaging Technologies*

Modern food packaging technologies are rapidly evolving, moving from a simple barrier approach to the concept of active and “smart” packaging. Today, packaging materials must not only protect the product from oxygen, moisture, light and microorganisms, but also actively influence the preservation of its quality, nutritional and sensory characteristics. In this context, molecular hydrogen (H_2) is a promising tool that can be integrated into various packaging solutions due to its unique antioxidant and antimicrobial properties, as well as high diffusion capacity [23].

One of the most studied areas is modified atmosphere packaging (MAP), where hydrogen is used in combination with traditional gases – nitrogen and carbon dioxide. Adding H_2 to MAP can significantly extend the shelf life of perishable products. Studies on strawberries have shown that hydrogen reduces the activity of enzymes responsible for browning, slows down the loss of antioxidants and preserves the freshness, taste and aroma of berries [20]. Similar results were obtained for fresh-cut apples, where H_2 prevented oxidative browning, preserved vitamin C and improved the texture of the product throughout the entire storage period [21].

Promising data have also been obtained for seafood. Experiments with dried shrimp demonstrated that MAP with hydrogen reduced the rate of lipid oxidation and rancid odor formation, significantly increasing shelf life under accelerated testing conditions [19]. These results highlight the versatility of H_2, applicable not only to fruits and vegetables, but also to protein products with a high degree of susceptibility to oxidative spoilage.

Much attention is paid to the development of active biopolymer films enriched with molecular hydrogen. Such materials work as "smart packaging": they create a physical barrier and simultaneously ensure product stabilization due to antioxidant and antimicrobial action. Biopolymer coatings with H_2 are especially in demand for meat and dairy products, where maximum slowdown of microbiological activity and reduction of the rate of oxidative processes are required. This approach opens up opportunities for abandoning synthetic preservatives and meets modern trends for "clean label" [19].

The use of micro- and nanobubble water enriched with hydrogen (HRW) deserves special attention. Nanobubbles have high stability and a large specific surface area, which ensures the gradual release of H_2 in the packaging environment. This allows for a long-term maintenance of the antioxidant and antimicrobial effect, reducing microbial contamination and preserving the nutritional value of products. Studies have shown that HRW slows down the loss of texture and nutrients in fruits and vegetables during storage [2]. Moreover, HRW can be used in combination with MAP and active coatings, creating a multi-level protection system.

Importantly, hydrogen packaging technologies combine efficiency and environmental friendliness. They reduce the use of synthetic additives, extend the shelf life of products, reduce food losses and increase consumer confidence in natural products. In addition, due to the flexibility of application, H_2 can be used for different product categories - from fresh fruits and vegetables to meat, dairy products and seafood. All this makes molecular hydrogen a powerful tool for the transition to sustainable and innovative storage technologies [10].

6. *Hydrogen in the processing of plant foods and beverages*

Processing of plant raw materials and beverages is one of the most dynamically developing sectors of the food industry. The key tasks here are the preservation of nutrients, aromatic compounds, color and texture of products, as well as ensuring their microbiological stability during long-term storage. In recent years, molecular hydrogen (H_2) has been actively considered as an innovative agent capable of significantly improving the quality of plant foods and beverages due to its antioxidant and antimicrobial action, as well as participation in metabolic stabilization [10].

One of the most significant areas is the use of H2 to stabilize juices, nectars, and functional beverages. Experiments have shown that enriching fruit juices with molecular hydrogen slows down the degradation of vitamin C and polyphenols, which are important biologically active components. At the same time, beverages retain their fresh taste and aroma longer, and their antioxidant potential remains high even after long-term storage [22]. Such results allow us to consider hydrogen as a promising alternative or supplement to traditional preservation methods.

Much attention is also paid to preserving the quality of freshly cut vegetables and greens. Hydrogen-rich water (HRW) treatment reduces the rate of darkening of leafy greens, cucumbers and tomatoes, reduces moisture loss and prevents the accumulation of toxic metabolites. At the same time, the cellular structure of tissues is preserved, which is directly related to the prolongation of freshness and an increase in the shelf life of products. In the conditions of the fresh-cut market, where visual appeal and nutritional value are critically important, such approaches have high practical potential [9].

Promising research is also being conducted in the field of storing grapes, berries and citrus fruits. Hydrogen exhibits the ability to slow down the processes of glycolysis and enzymatic darkening, reduce the activity of polyphenol oxidase and catalases, which has a positive effect on the preservation of color and aroma. In particular, when storing grapes, the use of HRW and modified media with H_2 made it possible to reduce weight loss and preserve antioxidant properties throughout the entire storage period [2].

An equally important area is winemaking and the production of fermented beverages. Hydrogen enrichment of wort or intermediate semi-finished products helps reduce oxidative reactions that often worsen the aromatic profile of wine and beer. It has also been shown that H_2 can modulate yeast activity, increase fermentation efficiency while reducing the accumulation of unwanted by-products [17]. These data open up new prospects for the use of H_2 in the high-value-added beverage industry.

The totality of available studies confirms that the use of molecular hydrogen in the processing of plant-based raw materials and beverages can become a breakthrough direction, combining the tasks of maintaining quality, increasing shelf life and forming functional value. In the long term, such technologies will reduce food losses, increase the competitiveness of products and bring to market new categories of beverages and plant-based products with improved characteristics [10].

Conclusion. Molecular hydrogen (H_2) has evolved in recent years from an object of fundamental medical research into a promising tool for the food industry. The unique properties of H_2, including selective antioxidant activity, the ability to reduce microbiological load and a positive effect on the preservation of organoleptic characteristics, make it a universal agent applicable in a wide range of food processing and storage segments.

The data reviewed show that hydrogen can be effectively used to extend the shelf life of meat, dairy and plant products, as well as to improve the stability of beverages. It demonstrates advantages in modified atmosphere packaging (MAP), in active biopolymer films and in technologies using hydrogen micro- and nanobubble water. Such approaches can significantly reduce the use of chemical preservatives, improve product quality and safety, and increase consumer confidence in clean label products.

Particular attention should be paid to the potential of hydrogen in the beverage and fresh-produce industries: the use of H_2 helps slow down browning, preserve texture, taste and antioxidant properties of products. In the long term, these technologies can make a significant contribution to reducing food losses and increasing the sustainability of the agro-industrial sector.

Despite the positive results, it should be noted that the field of application of molecular hydrogen in the food industry is at the stage of active development. For full implementation, large-scale research into the mechanisms of its action, standardization of technologies and assessment of economic feasibility are required. An important area will also be the development of a regulatory framework defining the permissible conditions and methods of using hydrogen in food technologies.

Molecular hydrogen is thus an innovative and environmentally friendly tool that can change the approach to ensuring the quality and safety of food products. Its implementation in the practice of processing, storage and packaging opens up new horizons for the creation of sustainable and functional solutions in the food industry of the future.

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