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## **THE EFFECT OF HEAT TREATMENT METHODS ON THE BIOAVAILABILITY OF MICRONUTRIENTS: AN INTERDISCIPLINARY ANALYSIS**

**Summary.** *The article presents an interdisciplinary analysis of the effect of various heat treatment methods on the bioavailability of micronutrients. The theoretical foundations of this process are revealed, including the stages of release, digestion, and assimilation of nutrients. The importance of the food matrix and the chemical form of nutrients for their digestibility is emphasized. Technological, biochemical, and biomedical approaches to assessing changes that occur when food is heated are analyzed. A classification of thermal treatments is proposed, and their main mechanisms of action on micronutrients are described. It has been found that water-soluble vitamins are most susceptible to losses during cooking, while carotenoids and fat-soluble compounds may exhibit increased bioavailability due to the destruction of cellular structures. The effect of processing depends on the type of product, its composition, and cooking conditions. The article provides a comparative analysis of various food groups. In particular, the changes occurring with vegetables, fruits, cereals, meat, fish, and eggs are considered. Based on the analysis, practical recommendations have been formulated on the choice of cooking methods that will preserve the nutritional value of products.*

**Key words:** *bioavailability, micronutrients, heat treatment, vitamins, minerals, food matrix, digestibility, culinary processing, nutritionology, nutritional value.*

**Relevance of the study.** The study of the effect of heat treatment on the bioavailability of micronutrients is of great interest, since nutrition plays a key role in maintaining human health. Micronutrients play an important role in regulating metabolic processes and preventing chronic diseases. However, a significant part of food products is subjected to heat treatment before consumption, which inevitably affects their nutritional composition and digestibility.

Scientific research confirms that different cooking methods affect the content and availability of micronutrients in different ways. Water-soluble vitamins, such as vitamin C, are particularly sensitive to temperature and can break down with prolonged heating. This is especially noticeable when cooking in water, when there is a significant leaching of vitamins. However, heat treatment can not only reduce, but also increase the bioavailability of certain substances. This occurs due to the destruction of cellular structures and the release of bound forms of nutrients, which increases their absorption by the body.

Modern research demonstrates that heat treatment can have both positive and negative effects on the quality of products. Some methods, such as boiling or frying, can lead to a loss of antioxidants and vitamins. At the same time, others, such as steaming or microwaving, contribute to better nutrient retention. The degree of change depends on the type of product, its chemical composition, and cooking conditions. This makes it difficult to develop universal recommendations that can be applied to all products.

The problem becomes particularly important when assessing not only the content of micronutrients but also their bioavailability, that is, their ability to be absorbed by the body. Research shows that heat treatment can significantly alter the bioavailability of minerals and other compounds, which must be taken into account when designing diets.

Thus, the relevance of this topic is due to the need for a deep and comprehensive study of the effect of various heat treatment methods on the

absorption of micronutrients. This analysis should take into account technological, biochemical, and biomedical aspects. The results of such studies are of great importance for the development of scientifically sound nutrition recommendations aimed at preserving the nutritional value of products and increasing the effectiveness of the prevention of nutrition-related diseases.

**The purpose of the study.** The purpose of this study is a comprehensive analysis of the effect of various heat treatment methods on the absorption of micronutrients by the body, taking into account technological, biochemical and physiological aspects.

**Materials and research methods.** The research is based on scientific publications and generalized results of experiments aimed at assessing the bioavailability of micronutrients in food products during various types of heat treatment.

The research applied methods of analysis and generalization of scientific literature, comparative and systematic analysis, as well as an interdisciplinary approach that includes elements of food technology, biochemistry and nutritionology.

**The results of the study.** Micronutrient bioavailability is the part of a substance that becomes available to the body after being released from the food matrix, digested, and absorbed. Bioaccessibility is also distinguished – the amount of nutrient that is released during digestion and can be absorbed by the body. Thus, the micronutrient content in a product does not always reflect its actual health benefits [5].

The bioavailability process includes several important steps: the release of nutrients from food, its dissolution in the gastrointestinal tract, passage through the intestinal epithelium and distribution in the body. To study these stages, both clinical studies and standardized in vitro digestive models are used, which allows for comparability of results.

The food matrix plays a key role in the process of nutrient absorption. In plant foods, micronutrients are usually found inside cells surrounded by cell walls, making them difficult to access. However, during mechanical and thermal treatment, these structures are destroyed, which promotes the release of nutrients, especially carotenoids and some minerals.

Bioavailability is strongly influenced by the chemical form of the substance and the composition of the food. For example, heme iron is absorbed better than non-heme iron. Vitamin C promotes its absorption, while phytates and polyphenols, on the contrary, reduce it. The absorption of zinc and calcium depends on their solubility and the presence of substances that may interfere with their absorption. And B vitamins require special transportation mechanisms.

Table 1 presents approximate data that are often used in theoretical models describing the bioavailability of various micronutrients.

*Table 1*

**Indicative indicators of micronutrient bioavailability and factors determining their assimilation**

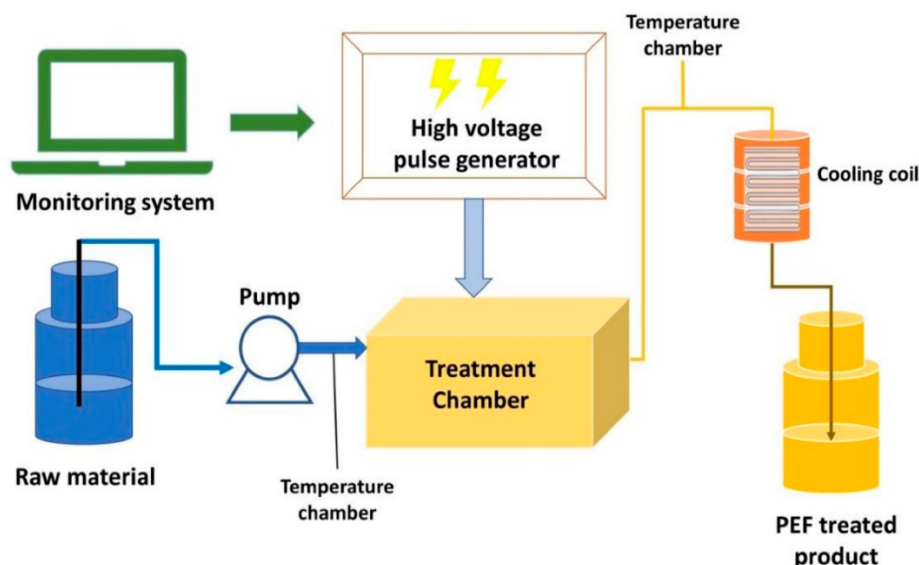
<b>The micronutrient</b>	<b>Approximate data on absorption / bioavailability</b>	<b>Theoretical significance</b>
Vitamin C	when 30-180 mg per day is ingested, about 70%-90% of the substance is absorbed, and at doses over 1000 mg per day, this indicator decreases to less than 50%	Absorption is dose-dependent and saturated
Iron	25%-30% from offal; 7%-9% from leafy vegetables; 4% from cereals; 2% from dried legumes	Bioavailability strongly depends on the form of iron and the composition of food.
Calcium	approximately 17%-55%, depending on the shape and matrix. In most studies, this figure is 20-30%	The same mineral is absorbed differently in different foods.
Folate	the bioavailability of folate found in foods is usually estimated at about 50% compared to folic acid	When calculating the need, it is important to distinguish between natural folate and folic acid

Vitamin B12	when taken orally at a dosage of 1.0 mcg, about 50% of the substance is absorbed from food additives, further, absorption decreases due to saturation of active transport, and only a small part – up to 1% – can be absorbed passively	For B12, the mechanism of transport is important, not just the content in food.
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Source: [4]

Interdisciplinary analysis of micronutrient bioavailability combines knowledge from various scientific fields such as food technology, biochemistry, physiology and nutritionology. As part of the technological approach, changes in the structure of food products under the influence of heat treatment are studied. Heating causes protein denaturation, destruction of cellular structures, and modification of the physico-chemical properties of the food matrix, which directly affects the release of micronutrients and their availability to digestive enzymes.

The figure below shows the general scheme of the product processing process using a pulsed electric field (PEF). The raw materials flow from the tank into the working chamber, where they are exposed to high-voltage electrical pulses generated by a special device. The process is controlled by a processing parameter monitoring system, which ensures its efficiency and accuracy. A temperature control and cooling system is used to prevent overheating. As a result of the treatment, a change in the permeability of cell membranes occurs, known as electroporation. This allows preserving the structure of the product and increasing the availability of intracellular components without significant thermal effects.



**Fig. 1. Diagram of processing of food raw materials by pulsed electric field (PEF) method [6]**

To systematize interdisciplinary approaches to the study of micronutrient bioavailability, we propose their comparative characteristics. In table 2, we have identified the key research objects and the factors that determine them.

*Table 2*

**Comparative characteristics of interdisciplinary approaches to the analysis of micronutrient bioavailability**

<b>Approach</b>	<b>The main object of the analysis</b>	<b>Key factors</b>
Technological	Product Structure	Temperature, time, type of treatment
Biochemical	Chemical changes	Oxidation, solubility, complexes
Medical and biological	Suction and transport	Enzymes, intestinal mechanisms
Hygienic	Food safety	Inactivation of microorganisms

*Source:* author's development

Thanks to an interdisciplinary approach, we can consider the bioavailability of micronutrients as a result of the complex effects of various factors: technological processes, chemical reactions and physiological

mechanisms. This understanding is necessary for an objective assessment of the effect of heat treatment on the nutritional value of products.

The heat treatment of products can be divided into three main groups: wet heating – includes cooking, steaming, steaming, and steaming; dry heating – includes baking, roasting, grilling and roasting; combined methods – such as stewing and brining, which combine roasting followed by cooking in liquid. Short-term and technological processing modes such as blanching, pasteurization and sterilization are also distinguished separately.

This division is important because the method of heat transfer, the presence of water and the duration of processing directly affect the preservation of micronutrients in products.

Table 3 shows the classification of heat treatment methods, as well as their description.

*Table 3*

**Classification of heat treatment methods and their characteristics**

<b>Method Group</b>	<b>Processing methods</b>	<b>Key Features</b>	<b>The most likely mechanism of micronutrient change</b>
Wet heating	Cooking, steaming, steaming	Heat transfer through water or steam	Leaching of water-soluble substances and partial softening of the substrate.
Dry heating	Baking, roasting, grilling, roasting	No direct contact with water, higher surface temperature	Oxidation, thermal degradation, and sometimes better preservation due to lack of leaching.
Combined methods	Extinguishing, tarpaulin	Combination of frying and subsequent heating in liquid	Exposure to temperature and leaching.
Short-term / technological modes	Blanching, pasteurization, sterilization	Processing with different heating intensity	Inactivation of enzymes and microorganisms with varying degrees of loss of thermolabile compounds.

*Source:* [1]

Water-soluble vitamins such as vitamin C and folic acid are particularly vulnerable to heat treatment. The loss of these vitamins is due to oxidation and conversion to water, and the loss is greater during cooking than during steaming or in the microwave. According to research, the vitamin C content in vegetables after processing can decrease by about 20%-50%, depending on the cooking method [3].

Fat-soluble vitamins and carotenoids are more resistant to heat, but changes in their content can be ambiguous. Heat treatment can reduce their concentration, but at the same time increase their availability by destroying cellular structures.

Minerals are resistant to high temperatures, but may partially dissolve in water during cooking. Therefore, their losses are mainly related to leaching rather than destruction.

Polyphenols and antioxidant compounds react differently to heat. Some of them are destroyed, but in some cases, their availability even increases due to the destruction of the food matrix [2].

Studies show that cooking and frying change the bioavailability of micronutrients the most, while steaming and baking tend to be less aggressive. In the course of studying various food ingredients, it was found that the total bioavailability of copper and zinc ranges from 76% to 80% in raw form, 50%-62% after steaming and baking, and 41%-50% after cooking and frying [7].

The effect of the treatment depends on the type of nutrients. In the case of selenium in fish, heat treatment does not lead to significant losses: its level remains between 64% and 100%. However, when it comes to iron and zinc in grains, not only heating is crucial, but also the phytate content, which can limit their absorption.

For carotenoids, the situation is reversed: heat treatment can reduce their content, but increase their digestibility. The bioavailability of lutein and zeaxanthin in eggs is higher than in plant sources due to the fat matrix.

Table 4 shows the specific effects of heat treatment on the main food groups.

*Table 4*

**The peculiarities of the effect of heat treatment on the main groups of food products**

<b>Product Group</b>	<b>The most significant processing effect</b>	<b>What you should pay attention to</b>
Vegetables and herbs	Reduction of the bioavailable fraction of trace elements during cooking and frying	It is preferable to use more gentle methods.
Fruits and berries	Destruction of anthocyanins and some phenolic compounds by heating	It is important to maintain a certain temperature and time.
Grains and legumes	The effect of phytate on Fe and Zn	Both the composition of the raw materials and the cooking method are important.
Meat	Changes in the proportion of heme iron	The heating method affects the retention of iron
Fish and seafood	Overall, high selenium preservation	The effect depends on the type of product
Dairy products and eggs	For eggs– high bioavailability of carotenoids	Consider the product matrix, not just the nutrient content

*Source:* author's development

Practical advice on choosing heat treatment methods is based on the desire to preserve the bioavailability of micronutrients and ensure food safety. For vegetables and herbs, it is recommended to use gentle cooking methods such as steaming, baking or short-term processing. These methods can minimize the loss of water-soluble vitamins. When cooking, it is better to use a minimum amount of water and avoid prolonged heating.

For foods that contain fat-soluble compounds such as carotenoids, vitamins A and E, moderate heat can be used, as it can increase their digestibility. When preparing cereals and legumes, it is important to take into account the phytate content. Combining these foods with those rich in vitamin C can improve iron absorption.

For cooking meat and fish, it is best to use methods that preserve minerals. For example, baking or stewing, but without prolonged heat treatment. When cooking eggs, it is important to take into account that their nutritional structure ensures high bioavailability of many compounds, even with standard cooking methods.

In general, the optimal solution is to choose processing modes that achieve a balance between preserving micronutrients, increasing their availability, and ensuring the microbiological safety of food.

**Conclusions.** Thus, heat treatment has different effects on the bioavailability of micronutrients. Water-soluble vitamins are subject to the greatest losses during cooking, while fat-soluble compounds and carotenoids can become more accessible due to the destruction of the food matrix. Minerals are preserved better, but they can be lost upon contact with water. It was found that when choosing the cooking method, the product features and the necessary nutrients should be taken into account. Gentle processing methods that ensure a balance between preserving nutritional value and product safety are considered the most effective.

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