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INTRODUCTION

In the modern world of agriculture, where livestock plays a key role in ensuring food security and economic development, effective management of the feed base is becoming a strategic priority. Animal feed is not just a raw material for feeding, but the foundation of the health, productivity and sustainability of livestock, poultry and other animals. According to FAO (Food and Agriculture Organization of the United Nations), more than 70% of livestock production costs are accounted for by feed, and its quality directly affects growth rates, milk yield and reproductive performance. However, in regions with a seasonal climate, such as Ukraine, where the summer surplus of greenery contrasts with the winter deficit, the problem of feed procurement and storage becomes critical. Here, the drying process comes to the fore - one of the oldest and most effective preservation methods, which allows you to turn fresh plant mass into a stable product resistant to microbial spoilage, loss of nutrients and external factors.

Drying of feed, as a technological process, is a complex interaction of physical, chemical and biological mechanisms, where the removal of moisture (from 70-90% to 10-15%) not only extends the shelf life to 12-24 months, but also concentrates nutrients, reduces weight for transportation and reduces the risks of contamination. In the context of global challenges such as climate change (increasing droughts and rains), energy shortages and sustainability requirements, drying takes on a new meaning. Traditional natural methods, although environmentally friendly, depend on the weather, leading to crop losses of up to 20-30% due to rain or mold. Artificial technologies, such as convective or freeze-drying, provide control, but require optimization to minimize energy consumption (up to 2000-3500 kJ/kg moisture) and degradation (carotene losses of 40-60%). In Ukraine, where livestock farming generates 15-20% of the agricultural sector's GDP, and feed losses reach 25% due to inefficient drying, the implementation of scientifically based approaches becomes imperative.

The relevance of the topic is due not only to economic, but also to environmental and social aspects. According to the State Statistics Service of Ukraine, up to 1-2 million tons of feed are lost annually due to spoilage, which is equivalent to 5-7 billion UAH of losses. Globally, according to IFPRI estimates, inefficient drying contributes to 10-15% of food losses in supply chains, exacerbating the food crisis. At the same time, innovations - from hybrid methods (microwave-vacuum drying) to modeling (ANN for kinetics prediction) - allow to increase efficiency by 30-50%, preserving >85% of bioactive substances. This is especially important for feed, where vitamin deficiency (A, E) reduces livestock productivity by 15-20%. The work is aimed at a systematic analysis of feed drying, with an emphasis on theoretical foundations, raw materials, methods, equipment and control, based on mass/energy balance equations (Fick, Arrhenius) and empirical models (Page), with graphical illustrations to visualize the influence of factors.

The aim of the study is to develop scientifically based recommendations for optimizing the drying processes of animal feed, taking into account their type, regional conditions and modern standards (DSTU, ISO). To achieve the goal, the following tasks were set: to analyze the theoretical foundations (physicochemical processes, classification of methods, mathematical models); to classify raw materials (coarse, juicy, grain, concentrated) and factors for choosing methods; to describe equipment (natural/artificial, vacuum, sublimation, IR); to optimize modes (T, v, t) depending on the feed; to assess quality control and problems (unevenness, losses, contamination).

The work was carried out within the framework of the research topic "Development of scientific and technological support for increasing soil fertility and rational use of the potential of bioresources" (State registration number 0124U000444).

CONTENT

CHAPTER 1. THEORETICAL BASIS OF ANIMAL FEED DRYING

1.1. The importance of drying in the technology of feed procurement and storage

Drying is one of the oldest and most effective methods of preserving animal feed, which plays a key role in the technology of its procurement and storage. This process involves the removal of moisture from raw materials, which allows to extend the shelf life of feeds, reduce nutrient losses and minimize the risks of contamination. In modern livestock farming, where ensuring a stable supply of quality feed is critical for animal productivity and health, drying is becoming an integral part of the production chain. According to research, drying feeds such as grasses, cereals and succulent forages allows to reduce the moisture content to a level below 10-15%, which makes them resistant to spoilage and suitable for long-term storage without the need for refrigeration. This is especially important in regions with seasonal crop fluctuations, where excess raw materials in the summer can be harvested for use in the winter. The rationale for drying is based on its multifaceted impact: from economic efficiency (reducing transportation and storage costs through weight reduction) to ensuring food safety in the field-to-tray chain. Next, we will consider key aspects of the impact of drying on microbiological stability, nutritional value and feed safety, based on scientific evidence.

Microbiological stability of feed is fundamental to prevent the development of pathogenic microorganisms that can cause animal disease and reduce animal performance. Drying directly affects this aspect by reducing water activity (aw), a key factor determining the possibility of microbial growth. Most bacteria require an aw of at least 0.87, while fungi and yeasts can grow at an aw of around 0.75 and some halophilic bacteria at 0.60. During drying, the aw of feed is reduced to a level below 0.7, which effectively inhibits the growth of pathogens such as Salmonella spp., Escherichia coli and Listeria monocytogenes. For example, studies on the drying of meat products, which can be extrapolated to animal feeds, have shown that reducing moisture content prevents microbial growth, extending shelf life without refrigeration.

Similarly, in dried animal feeds such as hay or grain, low moisture levels (below 10%) reduce the risk of mycotoxin formation produced by fungi of the genus Aspergillus and Penicillium, which often occur in humid storage conditions.

The rationale for this effect is supported by experimental data: in studies on drying food waste as an alternative feed for poultry, drying at temperatures of 155°C reduced the microbial load, including aerobic mesophilic bacteria and coliforms, to levels that meet feed safety standards. In the context of the preparation of feeds such as silage or grasses, natural or artificial drying prevents fermentation and putrefaction caused by anaerobic bacteria. However, insufficient drying (e.g. in high ambient humidity) can lead to residual contamination, as shown in studies on meat drying, where temperatures below 63°C do not completely eliminate pathogens. To optimize microbiological stability, it is recommended to combine drying with pretreatments such as blanching or the addition of organic acids, which enhance the antimicrobial effect and ensure stability during storage in different climatic zones.

Feed nutritional value is the preservation of key components such as proteins, carbohydrates, vitamins, minerals and fatty acids, which directly affect the growth, reproduction and health of animals. Drying helps to concentrate nutrients by removing water, which increases their density in dry matter. For example, in dried meat products, which serve as a model for protein feeds of animal origin, the process preserves proteins (up to 76 g/100 g dry weight), fats and minerals such as iron (up to 2.8 mg/100 g) and zinc (3.8 mg/100 g), satisfying a significant part of the daily needs of animals. In plant feeds such as grasses or grains, drying preserves carotenoids, B vitamins and amino acids by preventing their oxidation in a humid environment.

However, the impact on nutritional value depends on the drying method: low-temperature methods such as freeze-drying minimize the loss of heat-sensitive substances, unlike convective drying at high temperatures, which can cause protein denaturation and vitamin degradation. Studies show that freeze-drying preserves the amino acid profile better than hot air drying, where losses can reach 20-30% for vitamin C and carotene. In the context of animal feed, drying food waste as alternative ingredients preserves macronutrients (proteins, carbohydrates, lipids) at a level sufficient to replace corn in poultry diets, although with some reduction compared to fresh samples. The justification for the positive effect is confirmed by the fact that dried feeds support animal productivity: in tests with feeding dried feeds, productivity (growth, milk yield) was not inferior to control groups in 75-77% of cases. To minimize losses, it is recommended to optimize the regimes (temperature 40-60°C for sensitive feeds) and add antioxidants, which ensures a balance between stability and nutritional value.

Feed safety encompasses the absence of pathogens, toxins and harmful substances that can be transmitted to animals and ultimately to humans through animal products. Drying enhances safety by creating unfavourable conditions for microbes and toxins: reducing moisture prevents the formation of mycotoxins such as aflatoxins and ochratoxins, which are often found in wet feeds and cause immunotoxicity and carcinogenesis in animals. In studies with drying pet foods, dried products remained safe when stored up to 35°C, without compromising quality. Similarly, in dried meat feeds, open air drying reduces E. coli and coliform contamination, although controls are required to avoid exceeding standards (e.g. <10^5 CFU/g for bacteria).

The safety rationale is based on the reduction of contamination risks: drying reduces the levels of cadmium, arsenic and aflatoxins in food waste as feed, making it safe for animals. However, if stored incorrectly (high humidity), secondary contamination is possible, as in the case of mycotoxins in dried feed transferred from animal feed. To ensure safety, it is recommended to integrate drying with hygiene practices (HACCP), which minimizes the risks of food poisoning and maintains animal health. Overall, drying not only extends shelf life, but also increases safety, contributing to sustainable animal husbandry.

1.2. Physico-chemical processes during drying

Drying is the process of removing moisture from a solid material by evaporating it and removing the resulting vapor.

Dehydration of materials is usually carried out to improve the quality of the target product, prevent caking, reduce transportation costs, reduce corrosion of equipment and pipelines, and increase the calorific value (for fuels).

Due to the high heats of vaporization of liquids, drying, like evaporation, is a relatively expensive technological process. For this purpose, before drying, part of the moisture is removed by a cheaper mechanical method - filtration, pressing, centrifugation.

Depending on the drying method, dried materials can be conditionally divided into the following groups:

- liquid materials - true and colloidal solutions, emulsions and suspensions;
- pasty materials;
- solid dispersed materials that have flowability in a wet state (dusty, granular and lumpy);
- thin flexible materials (fabrics, films, paper, cardboard);
- artificial, massive, large-sized materials and products: ceramics, building construction elements, wood products;
- products that are subject to drying after priming, painting, gluing and other surface work.

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- convective drying (heat for the process is transferred to the material when it is in direct contact with a drying agent, such as heated air, topical and other gases);
- contact (conductive) drying (heat is transferred to the material through the wall separating them);
- radiation drying (heat is transmitted by infrared rays);
- dielectric drying (heat is released in the material as a result of the action of high-frequency currents on it);
- sublimation drying (drying of the material is carried out in a frozen state under a deep vacuum).

Convective and conductive drying are most often used in technology. The last three methods are special types and are used somewhat less frequently.

The drying process, like any mass transfer process, has a corresponding reverse process - the absorption by a solid material of moisture from the environment, which contains either moisture vapor or a mixture of moisture vapor with other gases. We denote the pressure of moisture vapor, when it is the only environment, by $P_{пар}$, and its partial pressure in a mixture with ambient gases is due to P_D.

At the same time, the moisture contained in the material corresponds to a certain equilibrium pressure of water vapor above the moist material being dried. $P_{мат}$.

The drying condition in this case is unevenness

$$P\text{мат} > P\text{пар або } P\text{мат} > PD. \qquad (1.1.)$$

Material moisture content that meets the condition $P_{мат} = P_{пар}$ $(P_{мат} = P_{D})$ meets the equilibrium condition.

The reverse process (sorption of moisture vapor from the environment by a solid material) is represented by the inequalities $P_{пар} > P_{мат}$ i $P_D > P_{мат}$.

Vapor pressure over the material being dried $P_{мат}$ зdepends on the moisture content of the material, the temperature and the nature of the moisture bond with the material. With increasing temperature and moisture content of the material, the value $P_{мат}$ increases (Fig. 1.1). In addition, the stronger the bond of moisture with the material, the lower, other things being equal, the moisture vapor pressure above this material.

There are several forms of moisture bonding with a material (if moisture is understood as water, then in order of decreasing bonding energy).

Chemically bound moisture - hydrated or crystallized, is part of the chemical compound itself and is not removed during drying. Its removal requires either high-temperature action (calcination) or chemical treatment.

Physico-chemically bound moisture (adsorptive and osmotic) - moisture located in micropores and bound to the material at the molecular level by adsorption and osmotic forces.

Mechanically (capillary) bound moisture that fills macro- and microcapillaries can be removed not only by drying, but also by mechanical action.

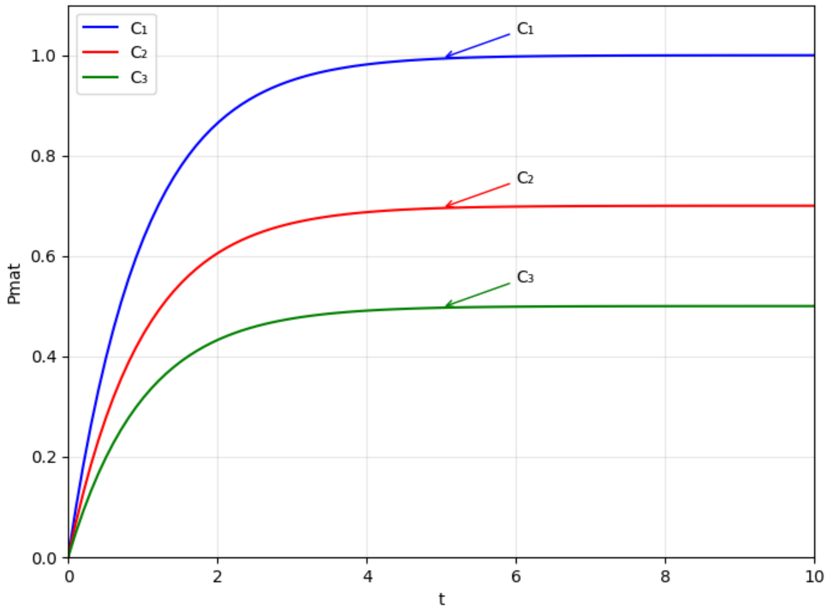


Fig. 1.1 Curves of equilibrium moisture content of the material: $P_{мат}$ – equilibrium pressure of water vapor over a moist material; c_1, c_2, c_3 – material humidity

Source: developed by the authors

The values of moisture concentrations in the material are used to describe the kinetics of the drying process, as well as to calculate the devices in which it is carried out.

The values of moisture concentrations are determined:

- moisture content c - the ratio of the mass of moisture contained in the material to the mass of wet material, kg/kg;
- moisture content x - the ratio of the mass of moisture contained in the material to the mass of dry material, kg/kg;
- relative humidity φ - the ratio of the amount of vapor in the gas to the maximum possible, corresponding to the saturated state at the same temperature and pressure, %.

Drying kinetics is determined by the change in time of the average moisture content of the material, which is usually constructed based on experimental data for each specific material (Fig. 1.2).

As follows from Fig. 1.2, the drying curve consists of two sections corresponding to its different periods, which are clearly visible in the graphical dependence of the drying rate on the moisture content of the material (Fig. 1.3).

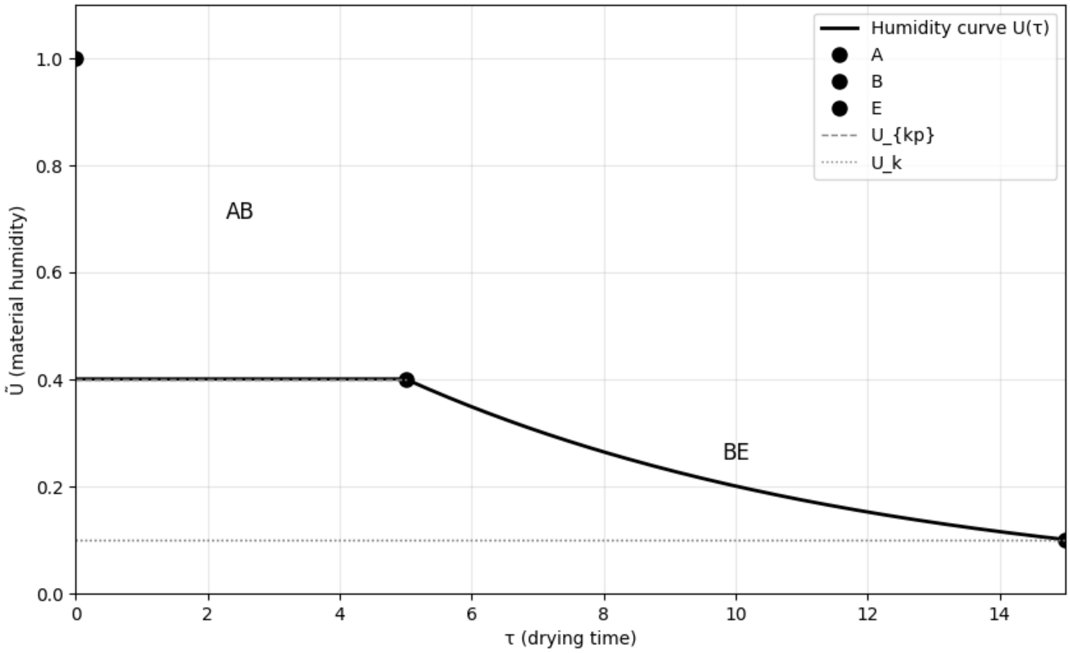


Fig. 1.2 Moisture curve of the material being dried: AB – period of constant drying rate; BE – period of decreasing drying rate

Source: developed by the authors

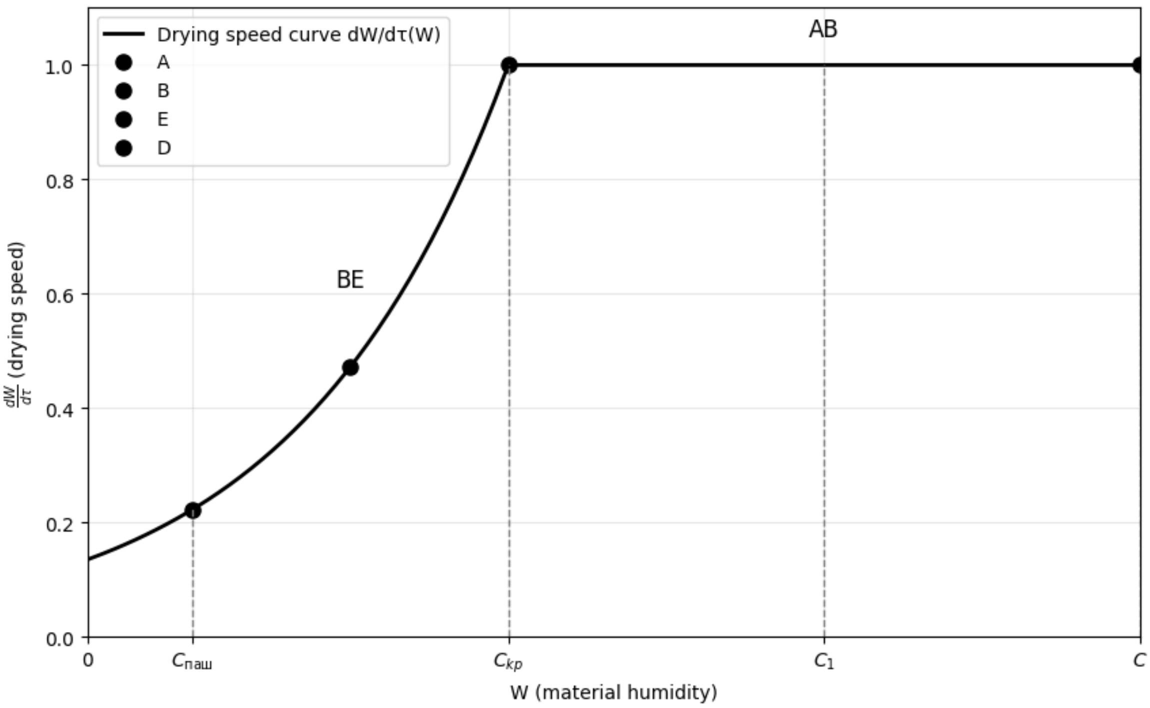


Fig. 1.3 Drying rate curve: AB - period of constant drying rate; BE - period of decreasing drying rate;

Source: developed by the authors

The first period (line AB) is the period of constant drying rate or external diffusion (surface evaporation).

During this period, the surface of the material is covered with moisture, which is provided by the high moisture content of the material at the beginning of drying and by the replacement of evaporated moisture by its diffusion from the inner layers. The rate of moisture diffusion is equal to the rate of water evaporation from the surface of the dried material. This means that the supply of water to the surface of the solid completely compensates for its removal from this surface. The rate of the total process during this period is limited by the rate of surface evaporation, i.e. the rate of removal of vapor molecules from the surface.

The kinetic equations for the first drying period can be written as

$$W = \beta_x F(x_{нас} - x)\tau_1 \tag{1.2}$$

or

$$W = \beta_p F(p_{нас} - p)\tau_1, \tag{1.3}$$

where W - the amount of evaporated liquid;

F - phase contact surface;

$x_{нас}$ - moisture content of saturated air under drying conditions;

x - actual (working) air moisture content; $p_{нас}$ - partial pressure of moisture under saturation conditions;

p -actual partial pressure of moisture vapor in the air;

β_x, β_p - mass transfer coefficients;

τ_1 - duration of the first drying period.

The factors that determine the drying rate in the first period are:

- gas humidity (the drier the gas, the greater the driving force of the process, and therefore the greater the drying rate);
- gas temperature (the higher the gas temperature, the higher the surface temperature of the material, and therefore, the greater the elasticity of saturated vapor and the higher the drying rate);
- gas velocity (the value of the mass transfer coefficient depends on the velocity of the gas flow, and an increase in velocity leads to an increase in flow turbulence, blowing, i.e. a decrease in the thickness of the boundary laminar gas layer and, consequently, an acceleration of the transfer of matter in it - vapor diffusion);
- evaporation surface (the evaporation rate increases in direct proportion to the evaporation surface, i.e. the drying rate increases when the material is ground, since the specific surface area increases).

The first drying period corresponds to the change in the moisture content of the material within $c_п$ - $c_{кр}$ (initial humidity - critical humidity).

The second period (line BE) is the period of falling drying rate or internal diffusion.

During this period, the supply of moisture to the outer surface of the dried material is not fast enough to compensate for the moisture evaporating from it, due to the increase in the depth of its extraction.

The change in the drying rate during this period depends on how quickly, compared to the evaporation rate, the moisture from the inner layers approaches the outer ones. This change depends on the form of the moisture bond with the material, the structure of the solid, the thickness of the piece, etc. It has been experimentally established that most often in the BE section the drying rate changes according to a linear law (see Fig. 1.3).

The kinetic equation for the second drying period can be written as

$$W = KF(c - c_{рівн})\tau_2 \tag{1.4}$$

where K - drying rate coefficient; c - the moisture content of the material at the moment; $c_{рівн}$ - equilibrium moisture content of the material; τ_2 - duration of the second drying period.

It should be noted that this kinetic law describes the phenomenon only approximately. Actual change in drying rate within the range of change in humidity $c_{кр} - c_{к}$ (critical humidity - ultimate humidity) may not follow a linear law (dashed lines in Fig. 1.3).

When during drying the surface of the dried material is covered with a crust, the process speed decreases and is expressed in the graph of the curve located below the straight line. In other cases, when the drying results in cracking of the dried material, and as a result - an increase in the surface of the phase contact, the drying speed increases and is expressed in the graph of the curve located above the straight line. $c_{кр} - c_{к}$.

Intensification of the second period of the drying process can be achieved by stirring the dried material, which promotes the mechanical transfer of moisture from the inner layers to the surface in contact with the drying agent.

Thus, for batch processes, the total drying time is τ consists of the drying duration in the first τ_1 and in the second τ_2 periods:

$$\tau = \tau_1 + \tau_2$$

Value τ, are determined from the equations (1.2) and (1.3)

$$\tau_1 = \frac{W}{\beta_p F \Delta p_{cep}}$$

or

$$\tau_1 = \frac{W}{\beta_p F \Delta p_{cep}}.$$

In these equations Δp_{cp} and Δx_{cp} - the average driving force of the process, which is determined by the formulas

$$\Delta p_{cp} = \frac{\Delta p_n - \Delta p_к}{\ln(\Delta p_n / \Delta p_к)};$$

$$(1.5)$$

$$\Delta x_{cp} = \frac{\Delta x_n - \Delta x_к}{\ln(\Delta x_n / \Delta x_к)},$$

where $\Delta p_n = (p_{нас} - p)_n$ - the initial difference between the partial pressure of saturated water vapor under drying conditions and the operating partial pressure; $\Delta p_к = (p_{нас} - p)_к$ - the final difference between the partial pressure of saturated water vapor under drying conditions and the operating partial pressure; $\Delta x_n = (x_{нас} - x)_n$ - the initial difference between the moisture content of saturated air under drying conditions and the working moisture content; $\Delta x_к = (x_{нас} - x)_к$ - final difference between the moisture content of saturated air under drying conditions and the working moisture content.

To determine the duration of the second drying period, equation (1.4) is used:

$$dW = Gdc = KF(c - c_{рівн})d\tau_2, \tag{1.6}$$

where G - amount of dried material, kg of dry matter.

From equation (1.1.6) we get:

$$\frac{dc}{c - c_{рівн}} = \frac{KF}{G} d\tau_2 \quad . \tag{1.7}$$

Integrating equation (1.1.7) within $c_{кр} - c_{к}$ and $0 - \tau$, we will get

$$\ln \frac{c - c_{рівн}}{c - c_{рівн}} = \frac{KF}{G}\tau_2 \quad \text{або} \quad \tau_2 = \frac{KF}{G} \ln \frac{c - c_{рівн}}{c - c_{рівн}} \quad . \tag{1.8}$$

Value $c_{кр}$ and $c_{к}$ are determined experimentally.[1]

1.3. Classification of drying methods

Drying used in food production is divided into two types: natural and artificial.

Natural drying occurs in the atmosphere of the surrounding air without additional heat input. Natural occurs in the open air without artificial heating and removal of the drying agent (air). An example of natural drying is the drying of salt in open sea water bodies. This method of drying is characterized by a significant duration, and the process is not regulated, and the final material obtained is still quite wet.

Artificial drying is carried out in special drying plants that provide intensive removal of moisture from the product. In food technology, artificial drying is used almost everywhere, i.e. drying with a heated drying agent (heated air, flue gases), which, after absorbing moisture from the material, is removed using special exhaust devices (fans). For most food industries, drying is one of the main processes, the purpose of which is to increase the stability of materials during storage, improve quality indicators, preserve, and reduce mass for transportation. In sugar beet production, granulated sugar, refined sugar, as well as production waste - pulp are dried. In alcohol production, production waste - wort, food and feed yeast are dried. Drying plays a significant role in brewing, where malt and production waste are dried. In starch-molasses production, the main product - starch is dried. Drying is used to produce powdered milk, dried fruits and vegetables. In the bakery, pasta and confectionery industries, bread is dried to produce crackers, pasta, and certain types of confectionery.

Depending on the method of supplying energy (heat), artificial drying can be of the following types:

- convective, which occurs due to the interaction of the product with the drying agent (air);
- contact (conductive), when heat is transferred to the product through the heating surface;
- radiation, which occurs due to heat transmitted by infrared radiation;
- dielectric, when the product is heated in a high and ultra-high frequency electromagnetic circuit;
- sublimation, which occurs under vacuum conditions; the product is in a frozen state.

Methods of drying wet materials differ mainly in the way of supplying heat and are determined by the physicochemical properties of these materials, as well as the form of their connection with moisture. The most common method is convective drying, which is characterized by direct contact of the material with a stream of heated gas (air, flue gases). Moisture evaporates using the heat of the heated gas, which simultaneously absorbs and removes the formed water vapor from the dryer.

Convective drying of products is long in time (3-10 hours), and the temperature used (+60...+750C) is optimal for enzymes and microorganisms, which leads to oxidation of vitamins, coloring and tanning substances, melanoid formation, deterioration of taste, aroma and color of the dried product. Fruits and vegetables dried in this way swell poorly and are ready for consumption only when boiled for 25-30 minutes.

Much less commonly, but also used in food production, is the contact (conductive) drying method, in which heat from the coolant (usually water vapor) is transferred to the material through a metal wall separating them.

For drying various painted metal products, cardboard products, as well as for drying food products in a thin layer, the thermoradiation method is used, in which heat is transferred by infrared rays.

Thick-leafed materials, as well as some fruits, if their shape needs to be preserved, are dried in a field of high-frequency currents. This method of drying is called high-frequency.

For very heat-sensitive materials, freeze-drying is used, in which moisture from the material in a frozen state passes into the vapor phase, bypassing the liquid phase (sublimates). The process is carried out in a deep vacuum.

The essence of this method is that the products are frozen in quick-freezing devices and in this state are placed in vacuum chambers, where moisture is removed from them, directly converting the ice into steam, which is sucked out of the chambers by a pump. In the place where the evaporated ice crystals were, steam remains, so these products have high porosity, have good swelling in water, and quickly boil when boiled. With this method of preservation, dried products retain their original properties well: shape, size, color, taste, aroma, vitamins. In this way, berries, vegetables, mushrooms, meat, poultry, fish, ready-made dishes from them, cheese are dried.

Dried products are hygroscopic, so they are packaged in moisture-proof containers and stored in dry rooms. Under these conditions, they can be stored for a long time.

The wet product is pre-frozen at a temperature of about -15...-18 °C. For most food products: cooling below -18 °C can lead to irreversible changes in protein substances. As a result, the quality of the products deteriorates, and the ability to absorb water is lost during rehydration, which is carried out to restore the original appearance, taste and shape of the product.

From the frozen product, which is placed on plates (with hot water circulating inside), in a sublimator under high vacuum, ice evaporates and the product is further cooled. When a significant part of the moisture in the form of steam has been removed from the product, heating with hot water is turned on and the material is dried at a temperature of about 30°C.

Products dried by freeze-drying retain their structure, color, taste, smell, nutritional properties, biological value (proteins, vitamins) and can be stored for a long time. This method is used to dry food concentrates, meat and dairy products, vegetables and fruits, but the method is expensive and complicated in terms of equipment. However, the costs of equipment and operation are fully justified by the high quality of the dried products.

Let's focus on some promising drying methods that have not yet become widespread.

The essence of "explosive" drying is that the prepared raw material is first dried to a humidity of 25...45% (depending on the type of product), and then loaded into a special apparatus - "gun", where it is subjected to an "explosion". The apparatus is a cylinder rotating around a horizontal axis. For its heating, there are gas burners located under it. On one side, the cylinder has a blind lid, and on the other - a hermetic lid that closes with a locking device. The product is loaded into the apparatus, the lid is closed, the cylinder is placed in a horizontal position, the heating and drive are turned on. After reaching a pressure in the cylinder of about 1.0...2.5 MPa, the pressure is released. This leads to the instant conversion of part of the moisture contained in the product into steam, as a result of which the product acquires a porous structure (the volume increases by 15...20 times). The recovery time of dried vegetables and potatoes during the specified processing method is 5...7 minutes. This process has not found wide application due to a number of disadvantages of the device: low productivity, periodicity of action, high noise level during operation.

The essence of the method of drying fruit and vegetable processing products (purees, pastes, concentrated juices) in a foamed state to obtain quick-recovery powders is that the pureed or concentrated liquid product is whipped into a stable foam using foam-stabilizing substances and dried to a moisture content of 2...4%. Foaming gives the product a more rigid structure and increases its surface to accelerate moisture diffusion. From the point of view of heat transfer, this method is not effective, because foam has low thermal conductivity. However, foam drying is a relatively fast drying method (the duration of the process for different products is from 3 to 20 minutes), which does not require high temperature. To stabilize the foam, emulsifiers are used (dry milk, agar, gelatin, starch, methylcellulose, etc.), and in some cases, air is blown through the whipped mass to improve foaming. Foam drying is most often carried out by a connective method on belt dryers. The dried product is crushed, sieved and packed in airtight containers. Juices and purees of raspberries, strawberries, apples, tomato puree, mashed potatoes, etc. are subjected to foam drying.

1.4. Mathematical models of drying processes: mass and energy balance equations, drying kinetics

In food technology, mass transfer processes are of great importance. The degree of their perfection is determined by the perfection of the entire technological line. Mass transfer processes include drying, extraction, crystallization, sorption and distillation (rectification). Common to all of them is the presence of two states or phases of components and the transfer of components from one phase to another. The transfer of substances is carried out first within one phase (internal transfer), then the substance overcomes the phase separation surface (external transfer) and is distributed within the second phase. Within each phase, substances are transferred mainly by molecular diffusion and convective transfer. Each phase may consist of one or more components.

The basic laws of the transfer of substances from one phase to another are determined by the theory of mass transfer, according to which the rate of mass transfer is proportional to the driving force. Its value can be determined based on the laws of phase equilibrium. The driving forces of mass transfer are considered to be differences in concentrations, temperatures, and pressures.

The amount of substance that passes within one phase to the phase boundary through the surface *F* perpendicular to the diffusion flow is determined by Fick's law

$$\mathrm{M} = -DF\Delta c\tau \;; \tag{1.9}$$

where *D* is the coefficient of proportionality (diffusion); Δc is the difference in concentrations (driving force); τ is the transfer time.

The total transfer of the amount of substance to the boundary (or from the boundary) of phase separation is determined by the mass transfer equation

$$M = \beta F(c_r - c_я)\tau \;; \tag{1.10}$$

where β is the coefficient of proportionality (mass transfer); $c_г$, $c_я$ — concentrations at the phase interface and inside (the core) of the flow.

The mass transfer coefficient, unlike the diffusion coefficient, is a kinetic characteristic and depends on the diffusion coefficient D (a physical constant), the flow rate υ, the density ρ and viscosity μ of the substance, and the geometric dimensions of the particles l_1, devices l_2 etc. In a generalized form, this dependence can be represented by the function

$$\beta = f(D, \upsilon, \rho, \mu, l_1, l_2 ...); \tag{1.11}$$

or in criterial form

$$Nu_D = A \mathrm{Re}^m \mathrm{Pr}_D^n \ ; \tag{1.12}$$

where $Nu_D = \frac{\beta l}{D}$, $\mathrm{Pr}_D = \frac{\nu}{D}$ -Nusselt and Prandtl diffusion numbers; Re = $\frac{\upsilon D}{\gamma}$ Reynolds number; l - defining geometric dimension; ν- kinematic viscosity coefficient.

The given relations indicate the analogies of heat and mass transfer processes, which allows us to generalize the methods of compiling mathematical models.

For the analysis of the operation of mass transfer processes, kinetic laws are very important, which have their own specific form for each type of mass transfer.

Since mass transfer processes are designed to separate or isolate (purify) a component (substance) from a mixture, then the main technological task of these processes can be formulated as obtaining a given amount of a certain substance of the required degree of purity (96% alcohol, 8% moisture content of yeast, etc.). In some cases (for example, during purification), the task can be formulated differently; the content of a harmful component in the main product or the content of a useful component in waste should not exceed the given (allowable) value.

The quality of the mass transfer process, provided that the main technological task is achieved, is assessed by the costs of heat, water, electricity, capital, operational, etc. The most general assessment is the costs of producing a unit of finished product.

On this basis, it is possible to formulate general goals for improving mass transfer processes: increasing the degree of separation purity and reducing specific costs per unit of production. This goal can be achieved by solving many individual problems for improving existing and developing new equipment, choosing optimal modes, increasing the stability and reliability of the equipment, automating control processes, etc. Such individual problems can be solved in many cases using mathematical models. Of all the mass transfer processes, one of the most common in food enterprises is the drying process. As an example, we will consider the solution of some problems for improving mass transfer using mathematical modeling methods, as well as the features of modeling the distillation process in connection with the specifics of the mass transfer of liquid and gas phases.

Drying is a typical mass transfer process in which moisture moves from the material being dried to the drying agent. Various food products, semi-finished products and raw materials (grain, malt, barley, feed and food yeast, starch, etc.) are subjected to drying. In some food industries, drying is the main technological process (production of crackers, powdered milk, egg powder, dried fruits and vegetables). The drying process is due to the application of heat to the product being dried, due to which moisture evaporates. As a drying agent, air, superheated steam and flue gases are used, which are saturated with moisture evaporated from the material being dried.

Drying of food products is carried out in drum, belt, shaft, spray, corridor, chamber drying, in installations with falling and fluidized beds, etc. These devices differ in design parameters, direction of the drying agent and the product being dried, pressure in the drying chamber. Regardless of the drying method and the design of the device, the drying installation is represented by the structural diagram shown in Fig. (1.4). Mandatory elements of the drying installation: air heater (fireplace, heater, etc.) 1, mixer 2,

drying chamber 3, a device for feeding the drying chamber or the hopper-accumulator of the material to be dried 4, a hopper-accumulator of the dry product 5. In some cases, drying processes with recirculation of the material to be dried or with recirculation of the drying agent are used.

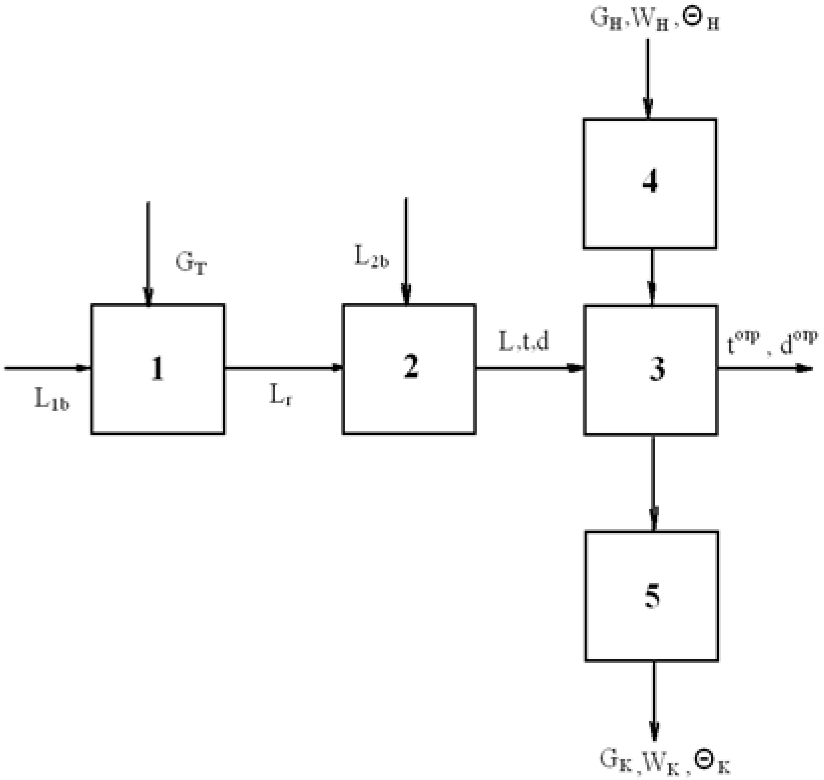


Fig. 1.4. Structural diagram of the drying plant

Source: Kyshenko V. D. Modeling of heat and mass transfer processes: lecture notes Kyiv: National University of Food Technologies, 2007. 117 p.

In this case, the drying unit is equipped to mix the source and recycle material and the drying agent. The most complex element from the point of view of compiling mathematical models is the drying chamber, where the drying process takes place, consisting of three stages: heating, drying and cooling. In some types of drying units, each stage is implemented by separate devices. The heater receives fuel Gt and air L1B, as a result of fuel combustion, hot gases are formed, which mix with atmospheric air L2B and form a drying agent with a flow rate L, temperature tc.a and moisture content d.

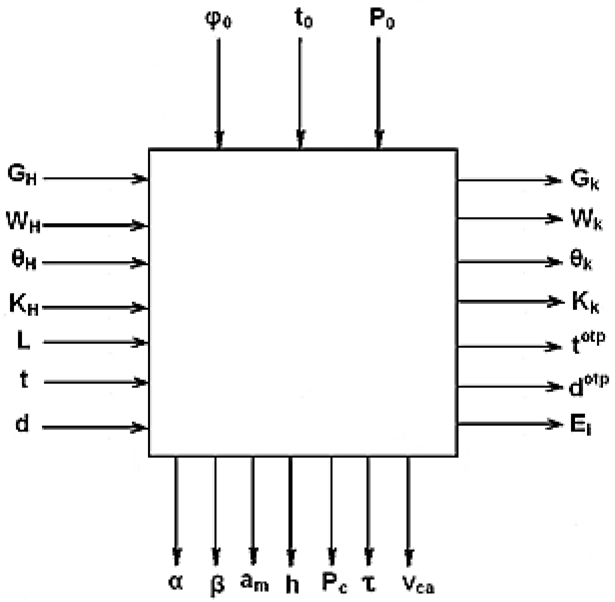


Fig. 1.5. Parametric diagram of the drying process.

Source: Kyshenko V. D. Modeling of heat and mass transfer processes: lecture notes Kyiv: National University of Food Technologies, 2007. 117 p.

The main parameters of the drying process are the characteristics of the material being dried and the drying agent (Fig. 1.5): flow rate GH, initial moisture content of the material yn (or humidity WH), its temperature tн, speed of movement υM, layer thickness hm in the drying chamber and its quality indicators kn. The drying agent is characterized by the flow rate L, temperature tca, moisture content d, etc. The process is also influenced by the characteristics of the environment: relative humidity φ0, temperature t0,, pressure P0.

The output parameters are the characteristics of the dried material after drying and the drying agent that has been used: final moisture content ik (humidity Wк), temperature tк, quality of the dry product kn, temperature, moisture content of the used drying agent. The output parameters can also be various characteristics (coefficients) of the heat and moisture exchange processes.α, β, αT , exposition τ, pressure Pc , drying agent speed in the layer υc. a etc. The initial characteristics are also the drying costs, which are determined by various efficiency criteria Ei: specific costs of fuel, electricity, labor, etc.

The main technological goal of the drying process is to ensure a given value of the moisture content of the product being dried while maintaining quality. The quality of the process is assessed by the specific costs per unit mass of removed moisture. The choice of controlled parameters and control influences is determined by the research objectives. Most often, the controlled parameters are humidity and drying costs. The quality of the dried material is, as a rule, a limitation. Since the quality of the product during drying is determined by the heating temperature of the material and exposure, then these parameters are the main limitations. The control influences are the parameters of the drying agent: flow rate (speed) and temperature, and sometimes the flow rate of the material being dried. Other input parameters are stabilized at the input or attributed to disturbing influences.

Various approaches and methods are used to establish relationships between input and output parameters. These relationships can be established analytically based on the use of material and energy balance equations, laws of hydromechanics, heat and mass transfer, etc. For example, to establish the relationship between the initial and final moisture content of the material being dried, the drying kinetics equation is used, to establish the relationship between the temperature of the drying agent and the dried material, the heat transfer equation is used. For more complex models that establish relationships between a larger number of parameters, it is necessary to jointly consider all of the listed analytical and experimental dependencies. Experimental methods for establishing relationships between parameters require the creation of a physical or full-scale model, in various plans, by active and passive methods.

The economic indicators of the drying process can be calculated based on technical characteristics obtained by direct measurement or calculation based on various models, taking into account the cost of equipment, existing standards and prices for work.

Since drying consists of three stages, when compiling mathematical models of heating, drying and cooling of the material being dried, the basic laws of mass and energy transfer are used. Since drying mainly involves convective mass transfer, it is necessary to take into account the basic laws of hydrodynamics.

When compiling mathematical models of heating, drying, and cooling of the material being dried, the equations describing these patterns are used in various forms.

To analyze the drying process, a system of differential equations describing heat and moisture transfer in moist bodies is usually taken as the basis.

$$\left.\begin{aligned}\frac{\partial u}{\partial \tau} &= k_{11}\nabla^2 u + k_{12}\nabla^2 t + k_{13}\nabla^2 P;\\ \frac{\partial t}{\partial \tau} &= k_{21}\nabla^2 u + k_{22}\nabla^2 t + k_{23}\nabla^2 P;\\ \frac{dP}{d\tau} &= k_{31}\nabla^2 u + k_{32}\nabla^2 t + k_{33}\nabla^2 P\end{aligned}\right\} \quad (1.13)$$

Odds k_{ij} are determined by a combination of thermodynamic and thermophysical characteristics of a moist body

$$k_{11} = a_m; \quad k_{12} = a_{m\delta}; \quad k_{13} = \frac{k_p}{\rho_0}; \quad k_{21} = \frac{2\varepsilon}{c}a_m; \quad k_{22} = a + \frac{\varepsilon r}{c}a_m\delta;$$

$$k_{23} = \varepsilon r = \frac{a_m}{c}\delta_p; \quad k_{31} = \frac{-\varepsilon a_m}{c_p}; \quad k_{32} = \frac{-\varepsilon a_m}{c_p}\delta; \quad k_{33} = \left(a_p - \frac{\varepsilon a_m}{c_p}\delta_p\right). \quad (1.14)$$

The following notations are additionally given here: $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ - the Laplace operator; $a = \frac{\lambda}{c_p}$ - thermal conductivity coefficient; a_m - moisture diffusion coefficient; δ - relative moisture thermal diffusion coefficient; δ_P - thermal gradient coefficient; ε - phase transformation criterion; r — specific heat of phase transformation; k_p - moisture filtration transfer coefficient; c - the specific heat capacity of the material is given; c_p - coefficient of capacity of moist air in a porous body; x, y, z - coordinates; ρ_0 - the density of the dry skeleton of a wet body.

For one-dimensional problems in the absence of a total pressure gradient, the system of equations simplifies to

$$c\rho_i \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda \frac{dt}{\partial x}\right) + \varepsilon r \rho_0 \frac{\partial u}{\partial \tau}$$

$$\frac{\partial u}{\partial \tau} = \frac{\partial}{\partial x}\left(a_m \frac{\partial u}{\partial x} + a_m\delta \frac{\partial t}{\partial x}\right); \quad (1.15)$$

All thermophysical and thermodynamic characteristics a_m, δ, λ, c, r, ε are functions of temperature t and moisture content.

In the above equations, sometimes the moisture content *u* replace with moisture transport potential $du = ct$, then the corresponding thermodynamic and thermophysical characteristics are divided by the mass density.

To solve the system of equations given above, it is necessary to know the distribution of temperatures and moisture contents inside the body at the initial moment of time (initial conditions), the geometric shape of the body, and the law of interaction between the environment and the surface of the body (boundary conditions). The set of initial and boundary conditions constitutes, in the simplest case, boundary conditions.

Boundary conditions can be specified in four ways. The boundary condition of the first kind consists in the problem of temperature distribution on the surface of the body $t_п$ in time, that is $t_n(\tau) = f(\tau)$ (Dirichlet problem), of the second kind – in specifying the heat flux density (derivative of temperature) for each point on the body surface as a function of time $q_п(\tau) = f(\tau)$ (Neumann problem), of the third kind – in the setting of the ambient temperature and the law of heat exchange between the body surface and the environment (mixed conditions)

$$q_n = \alpha[t_n(\tau) - t_c(\tau)] \tag{1.16}$$

where t_c -ambient temperature.

The boundary condition of the fourth kind corresponds to the heat exchange of a body with the environment according to the law of thermal conductivity or the case of heat exchange of touching solid bodies when their surface temperatures are the same (ideal thermal contact).

The temperature distribution inside the body at the initial time is given by the initial condition

$$t = (x, y, z, 0) == f(x, y, z). \tag{1.17}$$

With a uniform temperature distribution, the initial condition takes the form

$$T = (x, y, z, 0) = t_0 = \text{const}. \tag{1.18}$$

According to the uniqueness theorem, if some function $f(x, y, z, \tau)$ satisfies the differential equation, initial and boundary conditions, then it is the only solution to the problem.

The presence of specified boundary conditions allows, in the simplest cases, to obtain analytical solutions to the direct heat conduction problem, i.e., to find the function

$$T_n = f\,(x,\ в,\ z,\ \tau). \tag{1.19}$$

Similar to the boundary conditions of heat transfer, the interaction of the body surface with the environment during mass transfer can also be described by boundary conditions of four kinds. The boundary conditions of the first kind correspond to the case when the potential for diffusion mass transfer on the body surface is equal to the potential for mass transfer in the environment; the second kind correspond to the case of mass transfer during drying of wet bodies, when in the first period the drying intensity is constant, and in the second it decreases. Therefore, in the boundary conditions, the mass flux density of the substance is given as a function of time $g_m = f(\tau)$. In a separate case g_m = const.

The boundary conditions of the third kind are similar to the boundary conditions of heat transfer, and the boundary conditions of the fourth kind characterize the molecular heat transfer between two media. In the general case, the boundary conditions for a one-dimensional flow are written as

$$\left.\begin{aligned} -\lambda\left(\frac{\partial t}{\partial x}\right)_n + q_n(\tau) - r(1-\varepsilon)q_n(\tau) = 0 \\ a_m\rho_0\left(\frac{\partial u}{\partial x}\right)_n + a_m\rho_0\delta\left(\frac{\partial t}{\partial x}\right) + q_m(\tau) = 0 \end{aligned}\right\}; \tag{1.20}$$

where q_n, q_m — specific flux of heat and moisture on the surface, respectively.

Initial conditions for one-dimensional flow at τ = 0 have the form

$$m = f(x) \quad \text{and.} \quad t_M = f_1(x) \tag{1.21}$$

The system of equations (1.20) and the boundary conditions constitute a mathematical description of heat and mass transfer in moist bodies and in a binary vapor-gas medium (drying agent) during convective diffusion in liquids, etc. For moving media, it is necessary to introduce a term containing the velocity of the medium into the equation. The form of writing the boundary conditions depends on the type of heat and mass transfer, the geometric shape of the medium, and the selected coordinate system.

When constructing mathematical models of heating, drying, and cooling of a material, the given mathematical dependencies are simplified by introducing various assumptions, which, although they reduce the accuracy of mathematical models, allow us to represent complex processes using relatively simple and accessible methods and means.

Such assumptions may include replacing complex multidimensional bodies and spaces with one-dimensional ones: dividing spaces and bodies of complex shape into simple elements; invariance of thermophysical and thermodynamic characteristics in the considered ranges of temperature and moisture content changes; exclusion from the equations of terms that have a negligible effect on the final results; transformation of the coordinate system to simplify the form of the record.

Due to the complexity and lack of accuracy of such descriptions, as well as the absence or complexity of the method for solving systems of equations, simpler forms of describing drying processes are most often used.

Drying kinetics are represented by various forms of the drying curve. The most common form is the equation of A. V. Lykov

$$W = W_p + (W_H - W_p) \exp(-k\tau), \tag{1.22}$$

where W, W_p, W_H — current, equilibrium and initial moisture content of the material; k — drying coefficient, which is a function of the temperature and humidity of the environment, $k = f(t, \varphi)$.

In some cases, it is rational to use the following form of writing:

$$W = W_p - (W_H - W_p)\exp\left(-a + \frac{b}{2}\tau\right)\tau \; ; \tag{1.23}$$

where a, b — coefficients characterizing the relationship between moisture and the material.

The equilibrium humidity for a given material is a function of the temperature and relative humidity of the drying agent. $W_p = f(t, \varphi)$. Therefore, using the notation

$W_{y \cdot H}$ = W_H — W_p and $W_y = W - W_p$ (moisture removed), the drying kinetics is represented by an equation of the form

$$W_y = W_{y.H} \exp - \left\{ k(t,\varphi) \left(a + \frac{b}{2}\tau \right) \tau \right\} \tag{1.24}$$

In this equation $k\ (t,\ \varphi)$ characterizes the regime, and $\left(a + \frac{b}{2}\tau \right)\tau$ — moisture-material relationship. Both of these characteristics are established experimentally, assuming that the description of the drying curve is known. With known descriptions of kinetic patterns and numerical values constant for the study, analog and digital computers can be used.

By representing equation (1.23) or (1.24) in differential form and drawing up a structural diagram of the set of this differential equation on the AOM, one can obtain a model for studying kinetics. To solve this relatively simple problem in automatic control systems, a specialized computing device is used, which allows repeatedly solving the problems of calculating the drying kinetics when the initial moisture content of the product changes.

More complex are the models based on mathematical descriptions of the fields of moisture content and temperature of the product and drying agent in the form of a system of equations. As an example of compiling such mathematical models, let us consider the problem of determining the moisture content of grain during the drying process according to the mathematical description of the field of moisture content and temperatures compiled by V.I. Zhidko and A.S. Bomko. This description, together with the initial and boundary conditions, has the form

$$\left. \begin{array}{c} m\left(\dfrac{\partial^2 u}{\partial r^2} + \dfrac{1}{r} \cdot \dfrac{\partial u}{\partial r} \right) = 0 \\ \dfrac{\partial u}{\partial \tau} + \upsilon_3 \dfrac{\partial u}{\partial x} - a\dfrac{\partial t}{\partial \tau} + \upsilon_3 \dfrac{\partial t}{\partial x} + \dfrac{A(\upsilon_{c.a})}{c_3 \rho}\left(t - t_{c.a} \right) - \dfrac{\rho_3}{c_3}\left(\dfrac{\partial u}{\partial \tau} + \upsilon_3 \dfrac{\partial u}{\partial x} \right) = 0 \\ u(\tau, x) = \dfrac{2}{R^2} \displaystyle\int_0^R \tau u(\tau, x, r) \partial r \end{array} \right\} \tag{1.25}$$

with initials

$$\left.\begin{array}{c} t(\tau,0) = f(\tau); \\ t(\tau,0) = f(\tau); u(0,x,r) = u_0(x,r); \\ t(0,x) = f_2(x) \end{array}\right\} \tag{1.26}$$

and boundary conditions $u\ (\tau,\ 0,\ r) = u°\ (\tau,\ \mathrm{r})$

$$\frac{\partial u}{\partial r}(\tau,x,R) = \begin{cases} -\dfrac{B(t,\upsilon_{c.a})}{a_m(t)}(u_R - u_P), u_R \le u_r \\ -\dfrac{B(t,\upsilon_{c.a})}{a_m(t)}(u_R - u_p), u_R > u_r \end{cases} \tag{1.27}$$

where $\frac{\partial u}{\partial r}(\tau,x,R) = 0$ - symmetry condition; *R* - particle radius; *A, B* - empirical coefficients, *x, r* - coordinates along the length of the drying chamber and the radius of the grain. The given system of two equations describes the process of drying grain in dense and fluidized layers under the condition of cross-motion of the material and the drying agent. If the regime is not disturbed, i.e. the drying process occurs in a steady state and $\frac{\partial u}{\partial \tau} = 0;\ \frac{\partial t}{\partial \tau} = 0 -$ then the equation will take the form

$$\left.\begin{array}{c} \left(\dfrac{\partial^2 u}{\partial r^2} + \dfrac{1}{R}\dfrac{\partial u}{\partial r}\right); \\ \dfrac{\partial u}{\partial x} = \dfrac{a_m(t)}{\upsilon_3}\dfrac{\partial t}{\partial x} = \dfrac{A\upsilon_{c.a}}{c_3\rho_3\upsilon_3}(t_{c.a} - t) - \dfrac{2\rho B(t,\upsilon_{c.a})}{c_3\upsilon_3 R}(u_R - u_P) \\ \dfrac{\partial u}{\partial r}(x,0) = 0 \end{array}\right\} \tag{1.28}$$

$\frac{\partial u}{\partial r}(x,0) = 0$ (symmetry condition) with initial

$$u\ (0,\ r) = u_0\ (r);\quad t\ (0) = t_0; \tag{1.29}$$

and boundary conditions

$$\frac{\partial u}{\partial r}(x,R) = \left\{\begin{array}{l} -\dfrac{B(t,\upsilon_{c.a})}{a_m(t_з)}(u_R - u_P), u_R \le u_r \\ -\dfrac{B(t,\upsilon_{c.a})}{a_m(t)}(u_r - u_p), u_R > u_r \end{array}\right\} \tag{1.30}$$

When transitioning to the system of equations (1.29 – 1.31), the relationship between the average drying rate and the surface moisture content was taken into account.

$$\Delta u = \frac{2}{R^2}\int_0^R r\Delta u \partial r = \frac{2}{R}\cdot\frac{\partial u}{\partial r}\Big|_{r=R} \equiv \frac{2}{R}\frac{\partial u}{\partial R}\cdot\frac{\partial u}{\partial \tau} + \upsilon_3\frac{\partial u}{\partial x} - \frac{\partial u}{\partial x} - \frac{2B}{R}(u_R - u_p) \quad . \tag{1.31}$$

Using the method of straight lines, previously used to solve the problem of temperature distribution of coolants, we reduce the system of partial differential equations to a system of ordinary differential equations by writing down the finite-difference relations.

$$\frac{\partial u_k}{\partial r} = \frac{u_{k+1} - u_{k-1}}{2h};$$
$$\frac{\partial^2 u_k}{\partial r^2} = \frac{u_{k+1} + 2u_k + u_{k-1}}{R^2}, \tag{1.32}$$

where k = I, 2, 3…..n — 1; n — line number related to $r = R$; h — interval along the radius of the dried material.

Given that $r = kh$, we will get

$$(\Delta u)_k = \frac{1}{2h^2 k}\left[(2k+1)u_k - 4ku_k + (2k-1)u_{k-1}\right], \tag{1.33}$$

and for the straight line with the last number $k = n$

$$(\Delta u)_n = \frac{2}{n}\left(\frac{\partial u}{\partial R} - \frac{u_n - u_{n-1}}{n}\right) + \frac{1}{R}\cdot\frac{\partial u}{\partial r}, \tag{1.34}$$

where n —line number related to $r = R$..

If you put $n = R/4$, then the system of equations will have the form

$$\frac{\partial u_1}{\partial x} = \frac{a_m(t)}{\upsilon_3 R^2}(24u_2 - 24u_1);$$

$$\frac{\partial u_2}{\partial x} = \frac{a_m(t)}{\upsilon_3 R^2}(20u_3 - 32u_2 - 12u_1);$$

$$\frac{\partial u_3}{\partial x} = \frac{a_m(t)}{\upsilon_3 R^2}\left(\frac{5}{3}u_4 - 32u_3 - \frac{40}{3}u_2\right);$$

$$\frac{\partial u_4}{\partial x} = -\frac{9B(t_1, \upsilon_{c.a})}{\upsilon_3 R}(u_4 - u_p) + \frac{32a_m(t)}{\upsilon R^2}(u_3 - u_4);$$

$$\frac{\partial t}{\partial x} = \frac{A(\upsilon_{c.a})}{c_2 \rho_3 \upsilon_3}(t_{c.a} - t) - \frac{2\rho B(t_1, \upsilon_{c.a})}{c_3 \upsilon_3 R}(u_4 - u_5); \qquad (1.35)$$

with initial conditions

$$u\,(0) = u;$$

$$t(0) = t;$$

$$i=1, 2, 3, 4.$$

Applying the finite-difference method for the time coordinate, we obtain

$$\frac{\partial u}{\partial \tau} = \frac{u_{k+1} - u_k}{g} + 0(g);$$
$$\frac{\partial t}{\partial \tau} = \frac{t_{k+1} - t_k}{g} + 0(g) \qquad (1.36)$$

where g - інтервал часу.

After substitutions, the system of equations will look like

$$\frac{\partial u_{k,1}}{\partial \tau} = -\frac{\upsilon}{g}(u_{k,1} - u_{k-1,1}) + \frac{a_m t_3}{R^2}(24u_{k,2} - 24u_{k,1});$$

$$\frac{\partial u_{k,2}}{\partial \tau} = -\frac{\upsilon}{g}(u_{k,2} - u_{k-1,2}) + \frac{a_m t_3}{R^2}(20u_{k,3} - 32u_{k,2} + 12u_{k,1});$$

$$\frac{\partial u_{k,3}}{\partial \tau} = -\frac{\upsilon}{g}(u_{k,3} - u_{k-1,3}) + \frac{a_m t_3}{R^3}\left(\frac{56}{3}u_{k,4} - 32u_{k,3} + \frac{40}{3}u_{k,2}\right);$$

$$\frac{\partial u_{k,4}}{\partial \tau} = -\frac{\upsilon}{g}(u_{k,4} - u_{k-1,4}) + \frac{9b(t_3 \upsilon_{c.a})}{R}(u_{k,4} - u_k) + \frac{32a_m}{R^2}(u_{k,3} - u_{k,4});$$

$$\frac{\partial t_k}{\partial \tau} = -\frac{\upsilon}{g}(t_k - t_{k-1}) + \frac{A(\upsilon_c)}{c_3 \rho_3}(t_{c.a}^k - t_3) - \frac{2\rho B(t_{3,} \upsilon_{c.a})}{c_3 R}(u_{k,4} - u_p). \qquad (1.37)$$

Solving this system of equations under initial conditions $\begin{array}{l} u_{k,1}(0) = u_{0,k}; \\ t_{k,i}(0) = t_{0,k}; \end{array}$

$$i= 1, 2, 3, 4,$$

we will obtain the distribution of temperature and moisture content along the length of the drying chamber and in time.

The application of mathematical methods for optimizing drying processes is complicated by the lack of regularities in the coefficients in the systems of equations describing the drying process, the characteristics of the material and the drying agent, the complication of the equations when substituting the existing regularities, etc. This sometimes leads to the fact that it is impossible to apply accurate optimization methods. Replacing the variable coefficients of the system with constants reduces the accuracy of the mathematical description of the process, and in some cases leads to the loss of the connection between the controlled and controlling parameters, which excludes the possibility of optimization using a model based on the accepted form of the mathematical description.

In some cases, it is possible to solve specific direct problems, the distribution of temperature and humidity fields, using the system of equations (1.37), supplemented with appropriate boundary conditions, with respect to the variables y, t and P, provided that the coefficients kij and the coefficients of the boundary conditions are constant. One of such problems was considered in the previous section. When optimizing the system of equations of the form (1.37) together with the boundary conditions, it is necessary to solve it with respect to the selected optimality criterion, and then choose one of the existing optimization methods. It is also possible to use existing descriptions of the drying process of granular materials in a layer, using the concept of a “thin layer”. In this case, the description is presented in the form of a multidimensional system of algebraic equations. In this case, the difficulties of optimization do not decrease.

Thus, the problems of optimizing the convective drying process are associated with the need to solve systems of partial differential equations describing the drying process, the presence of technological and other restrictions, i.e. the complexity of the mathematical model of the drying process and the difficulties of experimentally determining constants in the equations of mathematical description. Optimization of drying processes using known kinetic laws simplifies the search for optimal solutions regardless of the properties and characteristics of the material being dried, i.e. it is a universal method.

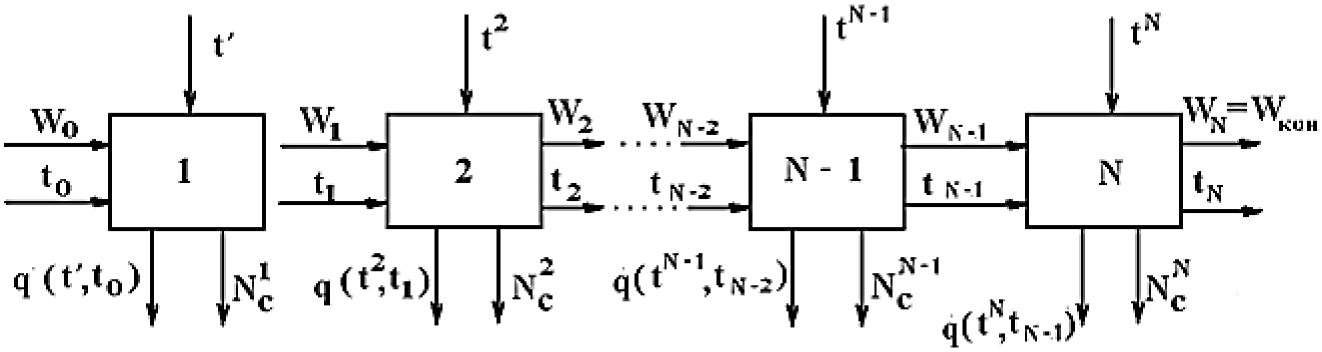


Fig. 1.6. Discrete multi-stage drying process.

Source: Kyshenko V. D. Modeling of heat and mass transfer processes: lecture notes Kyiv: National University of Food Technologies, 2007. 117 p.

Drying kinetics is determined by a number of parameters - temperature $t_{co,}$ relative humidity φ_1, drying agent speed $\upsilon_{c.\,a}$, initial humidity W_0 and layer thickness *h*. For a given drying method or a specific type of drying plant, with given design parameters, the number of factors determining the drying kinetics can be reduced. For example, when drying granular materials in a dense layer, the parameters *h* and $\upsilon_{c.\,a}$ determined by the design of the drying plant, a *t* - drying method and type of material. The moisture removal process depends only on W_0 and $t_{c.a}$, i.e. in this case humidity is a disturbing parameter, a $t_{c.o}$ - manager.

Usually, experimentally determined drying curves can be represented as a limiting case of a discrete multi-stage process, if a sufficiently small time interval is taken as a separate stage. Then, the dynamic programming method or the discrete maximum principle is used to solve the optimization problem of such a process.

In general terms, a multi-stage drying process can be represented by the diagram shown in (Fig. 1.6). Each stage, which represents the process flow over a relatively short period of time, is characterized by a certain value of the material moisture content at the inlet and outlet. Control parameter $t_{c.a.}$ at each stage can take a number of values in a certain temperature range. This parameter is used to optimize the variables W_i and $q\ (t_N)$. Variable $q\ (t_N)$ - optimization criterion, can characterize the costs at the *Nth* stage with the appropriate choice of the control parameter t_N when humidity changes within the range of W_H (W_0) to $W_{кін}$. As an optimality criterion, one can take, for example, the energy consumption for moisture removal.

Attempts to develop algorithms for optimizing drying modes using the drying curve are known. However, these algorithms are difficult or impossible to use due to the lack of necessary relationships between process parameters in a form acceptable for calculation.

To develop optimization algorithms for determining energy consumption, it is necessary to represent the change in humidity as a function of the parameters of the drying agent.

In addition, attempts have been made to apply economical methods of multifactorial experimental design to obtain these dependencies. In particular, these methods have obtained the regularities of the drying coefficient change for the first and second periods from some regime parameters in the form of linear regression dependencies. These formulas allow us to establish the value of the material moisture content in time. For calculations of the kinetics of multi-zone (step) drying and other conditions, these methods are unacceptable and have not been widely used for describing the kinetics. In this regard, we will develop such a form of description that would simplify the optimization procedure and increase the accuracy of the calculation.

In the general case, the kinetic curves of drying or heating of the product are represented as a function of the parameters that determine the initial state of the grain (humidity W_0 and temperature Θ_0), value of the control parameter (temperature of the drying agent t) and the current coordinate (time τ). Since the flow rate is usually constant, then the functions have the form

$$W = f(W_0, \Theta_0, t, \tau);$$
$$\Theta = f(W_0, \Theta_0, t, \tau). \tag{1.38}$$

Such dependencies allow for given W_0, t and Θ_0 calculate the moisture or temperature value of a material at any point in time.

The use of multifactorial experimental designs to obtain kinetic patterns of heating and drying is associated with some peculiarities. For example, the appearance of incompatible combinations at individual levels in the experimental designs is not always taken into account (the initial humidity cannot be lower than the current one, etc.). In addition, the duration of drying to a given final humidity, in experiments with different initial values of humidity and temperature of the product, varies within such limits that factorial designs become ineffective and the obtained regression equations inadequate. The exposure of drying when determining its modes and other calculations is most often unknown. These difficulties can be overcome if, with a known final humidity, the current humidity of the product W, expressed in relative units, is taken as the main kinetic parameter

$$W^* = \frac{(W_0 - W)}{(W_0 - W_k)}; \qquad (1.39)$$

Taking into account these features, we present the kinetic patterns as a dependence of the average drying rate N and the product temperature t on the following parameters:

$$N = f\,(W_0,\ \Theta_0,\ t,\ W^*);$$

$$\Theta_0 = f\,(W_0,\ \Theta_0,\ t,\ W^*) \qquad (1.40)$$

and we will draw up an appropriate experimental plan.

The drying exposure is determined from the expression

$$\tau = \frac{(W_0 - W)}{N}; \qquad (1.41)$$

The use of dependencies for calculating drying exposure and product temperature is possible only at a constant temperature of the drying agent during drying from W_0 to W (that is, from 0 to τ). If the dryer has several drying zones, that is, the temperature of the drying agent in each zone changes, then the description becomes significantly more complicated with an increase in the number of zones and is associated with a larger number of experiments, and also complicates the selection and compilation of a procedure for optimizing drying modes.

The multi-stage drying problem can be solved by including another parameter in the equation ( ) W_i — the initial reference point, i.e. the point on the drying curve that is the beginning of each stage (zone) of the process, where i — drying zone number. Instead of the initial grain temperature Θ_0 worth including Θ_i. In addition, the experimental plan should include non-absolute *W, a* relative, i.e. interval W_0 - W_1 expressed in relative units (fractions).

$$W_i^* = \frac{(W_0 - W_i)}{(W_0 - W_k)}; \tag{1.42}$$

Similarly, the factor W^* will have the form

$$W^* = \frac{(W_0 - W)}{(W_i - W_k)}; \tag{1.43}$$

Thus, the kinetics of drying and heating of products can be represented in the form of an equation of the type

$$y = f(W_0, W_i^*, \Theta_i, t, W^*); \tag{1.44}$$

In this case, the average drying rate is calculated from the humidity W_0 to the current humidity W:

$$N = \frac{(W_i - W)}{(\tau - \tau_i)}; \tag{1.45}$$

where τ_i - drying time corresponding to humidity W_i.

To increase accuracy and also for convenience of calculations in the left part of equation ( ), it is more expedient to use not the average drying and heating rates of the product from W_i to W, a magnitude

$$A = \frac{1}{N} = \frac{(\tau - \tau_i)}{(W_i - W)} \quad хв/\% \tag{1.46}$$

$$B = \frac{(\Theta - \Theta_i)}{(W_i - W)}, \quad {}^0C/\%; \tag{1.47}$$

The value *B* represents the ratio of the average heating rate of the product to Θ_i to Θ to medium drying speed from W_i to W. The drying exposure and product temperature are determined by the equations

$$\tau = \tau_i + A(W_i - W); \tag{1.48}$$

$$\Theta = A_i + B(W_i - W); \tag{1.49}$$

Taking into account the above, in order to obtain quantitative regularities in the drying of corn grain in a dense layer, a series of experiments was conducted on D - optimal plan type B_5. Grain layer thickness δ = 200 mm, drying agent speed υ = 0,4 m/s. Area of change of factors W_0, W_i^*, Θ, t and W^* limited by inequalities (here and now humidity is expressed per a. c. mass)

$$23\ \% \le W_0 \le 57\ \%, \qquad 0 \le W_i^* \le 0{,}8; \qquad 45\ °C \le \Theta_i \le 65\ °C, \quad (1.50)$$

$$80\ \% \le t \le 200\ \%, \qquad 0{,}1 \le W^* \le 1{,}0.$$

After processing the experimental data, regression equations were obtained and their statistical analysis was performed (calculation of variances, checking the significance of coefficients, assessment of the adequacy of models, etc.). The equations in the natural values of the factors have the form

$$A = 14{,}0099 + 0{,}06155\ W_0 + 7{,}92264 W_i^* - 0{,}28261\Theta_i;$$

$$- 0{,}05372\ t + 4{,}15838\ W^* - 0{,}00130 W_0^2 - 0{,}71225\ (W_i^*)^2 + 0{,}00176\Theta_i^2 + 0{,}0000972\ t^2 +$$

$$+ 0{,}38312\ (W^*)^2 + 0{,}03975 W_0 W_t + 0{,}000132 W_0\Theta_i + 0{,}000106 W_0\ t + 0{,}01230 W_0 W^* + 0{,}04803 W_i^*\Theta_i - - 0{,}03953 W_i^*\ t + 1{,}84424 W_i^*\ W^* + 0{,}000196\Theta_i\ t + 0{,}2414\Theta_i\ W^* - 0{,}02160 t^*;\ /\%;$$

$$B = -10{,}33849 + 0{,}05881 W_0 + 15{,}03633 W_i^* - 0{,}05705\Theta_i + 0{,}09091 t + 7{,}60176 W^*$$

$$+0{,}000441 W_0^2 - 6{,}98867\ (W_i^*)^2 - 0{,}00015\Theta_i^2 - 0{,}0000368 t^2 - 1{,}27952\ (W^*)^2 -$$

$$0{,}09451 W_0 W_i^* + 0{,}000\ 13\ 1 W_o\Theta_i - 0{,}00096 W_0 t - 0{,}04535 W_0 W^* + 0{,}03172 W_i^*\Theta_i -$$

$$0{,}00159 W_i\ t + 5{,}41831 W_i^*\ W^* - - 0{,}000278\Theta_i t + 0{,}00854\Theta_i W^* - 0{,}00368\ t\ W^*;\ °C/\%.$$

The obtained interpolation formulas are a convenient form for developing an optimization procedure, since this form of writing is invariant with respect to the initial conditions and kinetic parameters.

Calculations using equations (1.49) and (1.50) showed satisfactory agreement with experimental data. It follows that the representation of drying kinetics in dimensionless coordinates, invariant with respect to the initial product parameters and kinetic parameters, allows the use of multifactorial experimental designs to describe the kinetics, which provide a minimum number of experiments.

Interpolation formulas that describe the kinetics of heating and drying in dimensionless coordinates are not only an economical and convenient form of representing boundary conditions, but also allow for the creation of algorithms for optimizing multi-stage drying modes.

Let us outline the procedure for compiling one of the possible algorithms for optimizing the grain drying process using the above descriptions of kinetics.

To develop an algorithm, we will present a multi-stage drying process as a diagram (Fig. 1.7). Each stage is characterized by certain values of product moisture at the inlet and outlet. The control parameter - the temperature of the drying agent - at each stage can take a number of values in a certain temperature range.

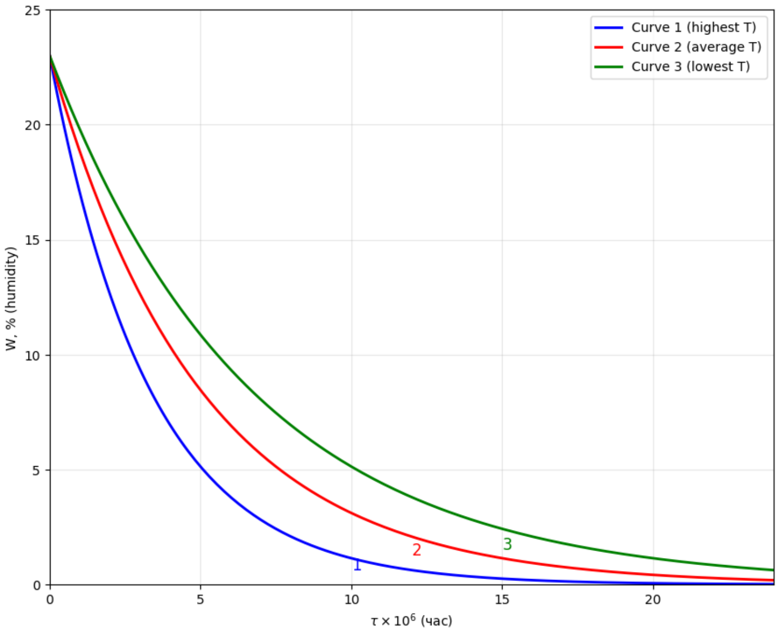


Fig. 1.7. Drying curves at different drying agent temperatures.

Source: developed by the authors.

The drying optimization problem is formulated as follows: for a given drying exposure, determine such values of the state parameter (product moisture content) and the control parameter (drying agent temperature) at each stage of the process that the heat consumption is minimal. To solve the problem, we use the drying curves $W = f$ (τ) (Fig. 1.8).

To determine the function $W = f(\tau)$, which corresponds to the optimal regime, the plane $W — \tau$ is divided along the time axis into N parts (stages) by lines

$$0 = \tau 0 < \tau 1 < \tau 2 < \tau j < \tau N - 1 < \tau N = \tau k \tag{1.51}$$

Then the graphs of the functions $W = f(\tau)$ can be represented graphically in the form (Fig. 1.8) of broken lines with vertices on the lines τ_j = const.

For lines connecting points $(Wi, j-1;\ \tau i, j-1)$ and $Ws, j;\ \tau s, j$ (i - entrance number, s - exit number from the *jth* stage), scalar quantities can be defined $q_{i,s}(j)$, which express the heat consumption for reducing humidity from W_i to W_s ($W_i > W_s$) at the *jth* stage of the drying process. In the case of uniform distribution along the axis τ value $\tau_{i,s}$ (j) depend on the drying speed $N = \frac{dW}{d\tau}$ and the drying agent temperatures t and do not depend on the stage number.

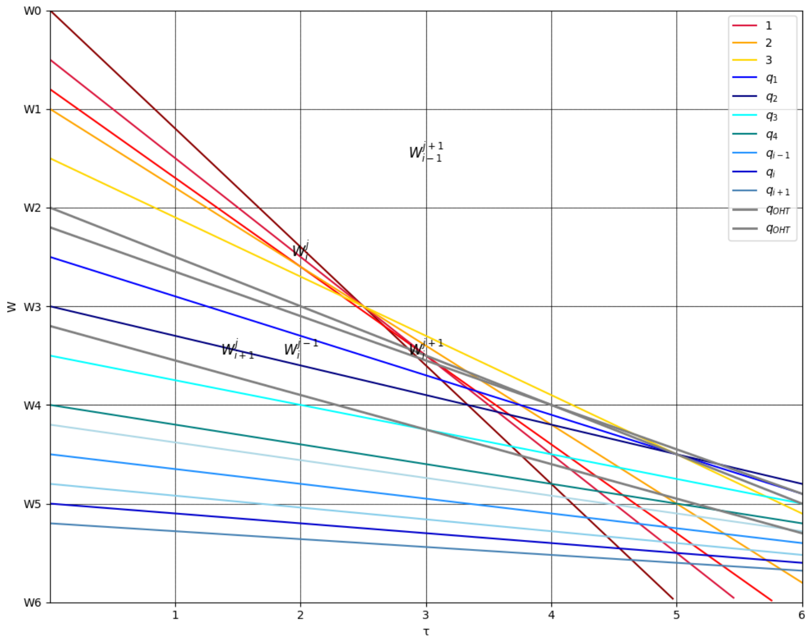


Fig. 1.8. Construction of a grid on the W (τ) plane to represent drying kinetics in tabular form.

Source: developed by the authors.

The heat consumption at each *jth* stage is determined from the expression

$$q = LJ\Delta\tau \text{ ;kJ,} \quad (1.52)$$

where L, J - consumption and enthalpy of the drying agent, kg/min and kJ/kg s. in; τ- drying duration, min.

The value of L is determined by the formula

$$L = 60Fv\rho, \text{ кг/хв,} \quad (1.53)$$

where F - cross-sectional area of the drying chamber (cassette), m^2; v and ρ — speed and density of the drying agent, m/s and kg/m^3.

The density of the drying agent is determined with sufficient accuracy for practical calculations by the formula

$$\rho = (1{,}293 \cdot 273)/(273 + t), \text{kg/m}^3.$$

The enthalpy value can be calculated using the well-known formula

$$J = 1{,}004e + 0{,}00I\, d\, (2500 + 1{,}84\, t)\ kJ/kg,\ s.\ in.,$$

where d - moisture content of the drying agent, g/kg dry matter ($d =$ 10 g/kg s. v.).

After substituting the drying unit parameters and the values L, ρ and J from the known relations the formula for determining heat consumption has the form

$$Q = \frac{(1662{,}578 + 67{,}993)}{273 + t} \text{ ;kJ.} \quad (1.54)$$

For a specific *jth* stage $\Delta\tau = \tau_j - \tau_{j-1}$ given, therefore $q_{i,s} = (j) = f(t)$. To determine the temperature of the drying agent t when changing from humidity $W(i)$ to the humidity $W(s)$ an equation is needed that relates the intensity of moisture exchange at the stage with the main transfer parameters, i.e. the equation $A = f(W_0, W_i, \Theta_i, t, W_s)$, a specific type of which is ( ).

In equation (1.55) A has the form

$$A = \frac{(\tau_j - \tau_{j-1})}{(W_i - W_s)} ;\ \text{хв}/\% \quad (1.55)$$

where W_0 - initial moisture content of the product, % ;

W_{ij}*, W_s*, - relative wetlands, which depend on W_i and W_s;

$$W_i^* = \frac{(W_0 - W_i)}{(W_0 - W_k)} \; ; \qquad W_s^* = \frac{(W_i - W_s)}{(W_i - W_k)} \; ; \tag{1.56}$$

where W_k - final moisture content, % ; Θ_i- grain temperature at the entrance to the stage, ^{0}C.

Equation (1.56) is valid in the range W_0 = 23...57 %; W_i^* = 0...0,8; Θ_i = 45...65°C, t = 80... 200 °C, W_s^* = = 0,1...1,0.

After calculations and substituting the value of A into equation (1.56), we determine the temperature of the drying agent, and then the heat consumption $q_{i,s}$. Similarly, we determine the heat consumption during transitions between other points. When calculating Q, we take into account the temperature of the grain at the entrance to the *jth* stage, determined at the previous stage from the equation of the type

$$\Theta_s = \Theta_i + B(W_i - W_s) \; ; \text{°C} \tag{1.57}$$

де $B = f\,(W_0, W_i, \Theta_i, t, W_s), \; {}^0C/\%$.

The value of B is determined from equation (1.57), in which

$$B = \frac{(\Theta_i - \Theta_s)}{(W_i - W_s)} \; ; \; {}^0C/\% \tag{1.58}$$

The range of factors is similar to equation (1.58).

The description of kinetics in dimensionless coordinates simplifies the optimization procedure and increases the accuracy of calculations at the final stage.

The resulting heat consumption Q of the entire multi-stage process is determined as an additive function of the costs obtained by summing $q_{i,s}$ all stages

$$Q = \sum_{j=1}^{N} q_{i,s(j)} \; . \tag{1.59}$$

According to the optimality principle underlying dynamic programming, optimization begins with the stage beyond which the process does not exist. In our case, these stages are the first *(j = 1)* and the last *(j = N)*. Optimization of drying is possible only from the first stage, because the values of the input parameters W_i and

Θ_i each subsequent stage can be determined only if the direction of calculations coincides with the direction of the process. After determining the optimal control for all possible output states of this stage, we proceed to determine the optimal equation for the next stage. Since for stage $j = 1$ there is no previous stage, then the optimality principle implies that any choice at the first stage can be optimal

$$q_{0,s}^{onm} = q_{0,s}\ ; \qquad (1 \le s \le n). \tag{1.60}$$

At stage $j = 2$, the optimal transition from point $(W_0,\ \tau_0)$ to the point $(W_s,\ \tau_j)$ will occur at heat consumption equal to the minimum of the numbers $\left[q_{i,s}(2) + q_{0,s}^{onm}(1)\right]$ Then for all subsequent stages we write the recurrence relation

$$q_{0,s}^{onm}(j) = \min\left[q_{i,s}(j) + q_{0,s}^{onm}(1)\right] \qquad (j = 1,2, \ldots, N). \tag{1.61}$$

The points $(i,\ s)$ obtained when searching for the minimum cost determine the trajectory of the optimal transition to the *jth* stage, started at the point $(W_0,\ \tau_0)$. Thus, for each stage, an optimal value can be found $q_{0,s}^{onm}(j)$ and dots $(i,\ s)$, corresponding to this optimal process trajectory. This allows for optimization of drying processes according to kinetic laws, presented in the form of interpolation formulas.

The structural diagram of the algorithm for optimizing the drying process according to kinetic laws with one control parameter is shown in Fig. (1.9). The procedure for implementing this algorithm has its own characteristics.

Before starting the solution, initial information (block 1) containing data on the initial parameters of the product (W_0 and Θ_0), drying agent temperature limitations ($t_{\min}$ i $t_{\max}$) and product temperature (Θ_g), the number of stages (N) and the duration of each of them (for a specific dryer), the required accuracy of calculations and other data ε.

This organization of the program allows to significantly reduce the required amount of machine memory. In this case, only two arrays of memory cells are used to store intermediate information. q_j and q_{j-1}, necessary to fill in the optimization results at the considered and previous stages.

The functions of the program blocks are as follows. Blocks *2-12* are intended to prepare the optimization program for calculation, for which a unit is sent to the stage counter cell (block *2*). Block *3* prepares the array [q_{j-1}], in which the results of the calculations of the previous stage are stored and where zero values are sent before the solution begins, which corresponds to the absence of a process outside the first stage (i.e., conditionally $f_0\ (x_0) = 0$).

Block *3* assigns the values of the initial material parameters W_0 and t_0 all *j-th* values of the first stage input and are sent to the array q_j ,as well as the meaning q_{max} = 10^9 kJ, in which the minimum values of the optimality criterion of the optimizing stage are placed.

Blocks *4-13* calculate the maximum $W_s^{\max}$ and minimal $W_s^{\min}$ humidity values that are necessary to determine the limits of change W_s and the interval of breakdown along the humidity axis. To determine the upper limit (W_s^{max}) in blocks *4 - 6*, along the humidity axis at the entrance to the *jth* stage, point *i* is determined, to which there is an optimal transition from point (W_0, t_0), and then in block *8* the value is calculated $W_s^{\max} = \frac{f}{t_{\min}^{c.a}}$. Similarly calculated $W_s^{\min}$ (blocks *9—13)*.

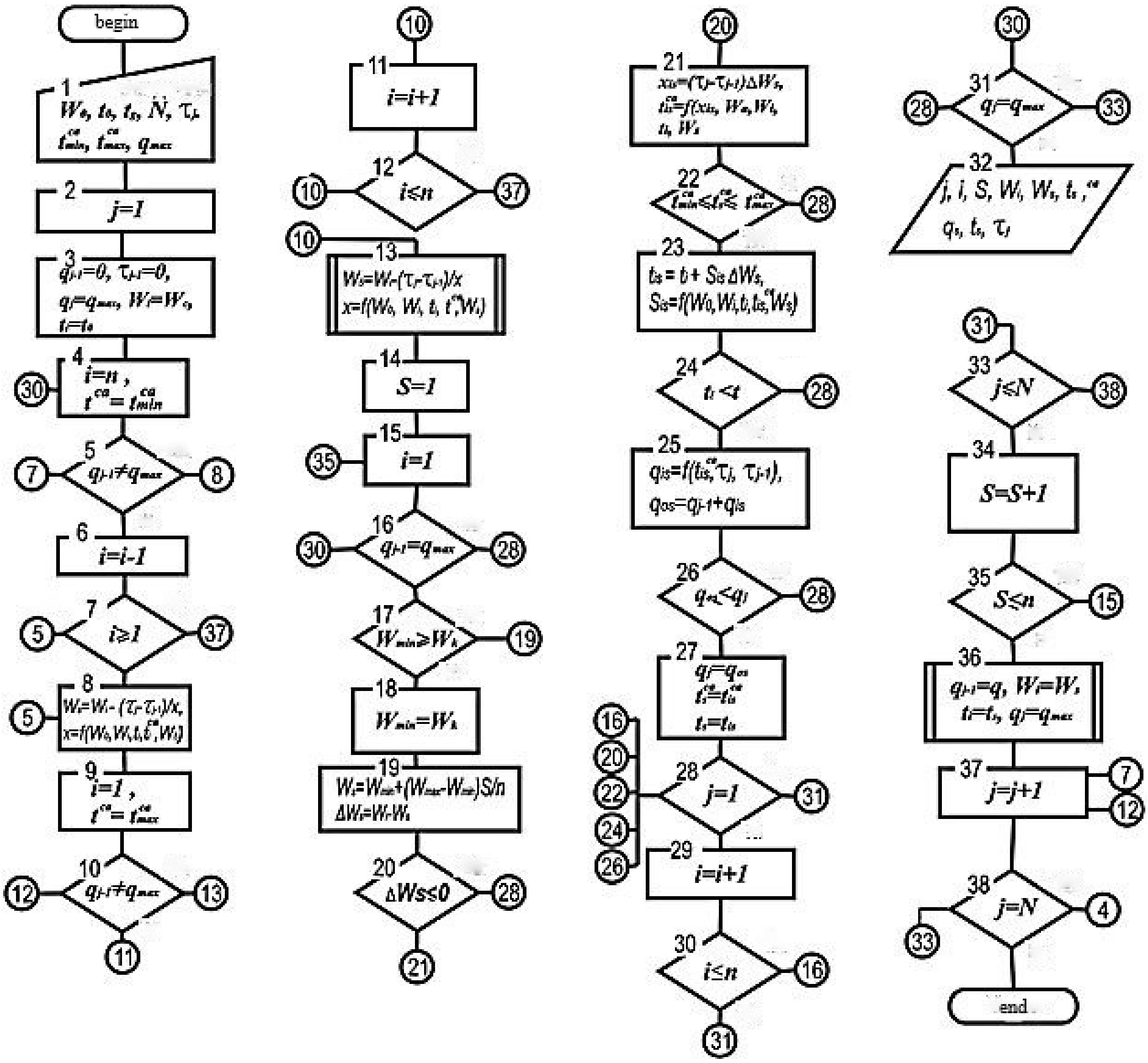


Fig. 1.9. Block diagram of the drying process optimization algorithm.

Source: Kyshenko V. D. Modeling of heat and mass transfer processes: lecture notes Kyiv: National University of Food Technologies, 2007. 117 p.

In blocks *14* and *15*, the first of all possible input states (point *i*) and output states (point *s*) at stage j are prepared for calculation. In this case, if at point $i = 1$ (output of the previous stage) there was no optimal transition, then control from block *15* is transferred to block *28*, where the following values of the material parameters at the input to the stage (the next point *i*) are prepared for calculation. In the opposite case, in block *19*, the value of humidity at the output is calculated. W_s^j wetland ΔW_s^j and if $\Delta W_s^j >$ 0 (block *20*), then the block subroutine *21* by equation $x = f(W_0, W_f, t_i,$

t^{ca}, W_s) the temperature of the drying agent is calculated t_{is}^{ca} when moving from point i to point s (drying from humidity W_i to humidity W_s).

After calculation t_{is}^{ca} block *22* it is checked whether the calculated result has not been achieved t_{is}^{ca} temperature value outside the detection range $(t_{\min}^{ca} \le t_{is}^{ca} \le t_{\max}^{ca})$. If t_{is}^{ca} is within the permissible region, then by block *23* according to equations

$$S = f\,(W0, Wi, ti, tis, Ws) \quad \text{i} \quad tis = t + S\, is\, \Delta Ws \tag{1.62}$$

the temperature of the material at the end of the stage (at point s) is calculated

$$ts = f\,(W0, Wi, ti, tca, Ws). \tag{1.63}$$

Resulting value t_s in the block *24* compared with the maximum permissible heating $t_{доп}$. If $t_s \le t_{доп}$, then block 25 calculates the heat consumption $q_{is} = f\,(t_{is}^{ca}$, $\Delta\tau$). If there is no moisture between i and s (ΔW_s^i = 0), drying agent temperature t_{is}^{ca} goes beyond the detection range, and heating the grain t_s exceeds the permissible temperature $t_{доп}$,then control from blocks *20*, *22* and *24* is transferred to block *28*, where the following stage input values are prepared for calculation (W_i), (j = 1, block *28*), in which the calculation cycles are organized according to the principle of optimality only by the stage output values W_s at $W_i = W_0$ = const, and the last stage (j = N, block *33)*,on which calculations are performed for only one value $W_s = W_k$ = 16 *%* when searching through all W_i. By value i in block *25*, in addition to calculating q_{is} sampling from an array q_{j-1} the minimum value of the optimality criterion of the previous stage, which determines in sum with the estimate q_{is} the value of the optimality criterion of a given stage, i.e. a process that includes, along with the previous stages, and is optimized at this moment. The result obtained $q_{is}^{j} + q_{0i}^{j-1}$ in block *26* is compared with the value q_{0s}^{j}, which was stored up to this point in the corresponding cell of the array q_1.

If the value is found again $q_{0s}^{j} = q_{is}^{j} + q_{0i}^{j-1}$ less than before, it means that the management t_{is}^{j} better than the one at which the previous value was obtained q_{0s}^{j}, and a new meaning q_{0s}^{j} is written to an array q_j in place of the previous one in the block *27.* At the same time, the control is memorized in the same block. t_{is}^{ca} *,* which is then printed in block *32*. In the same block, the values are printed W_i, W_s, t_{is}^{ca} numbers *j*, *i*, *s* and the corresponding value of heat consumption q_{0s}.

In the case when the value of the optimality criterion is found again $q_{is}^{j} + q_{0i}^{j-1}$ turns out to be greater than the previous one, then control of the calculation program from block *26* is transferred to block *28*, where the next input value of the *jth* stage is prepared for calculation — W_i. If for everyone *i* — *s*-non-occurrences (at W_s = const) block conditions are not met *16, 20, 22* and *24,* i.e. not calculated q_j, then the results are not printed and control is transferred from block *31* to block *33* to prepare for the calculation of the next value W_s.

After completing the iteration through all output values W_s and printing values *j*, *i,* s, W_i, W_s, t_s, t_{is}^{ca} $q_{0\,s}$, in block *35*, the output values of stage *s* are transferred to the input values of the next stage i $(W_i^{j-1} = W_s^{j};\ t_i^{j-1} = t_s^{j};\quad q_{0i}^{j-1} = q_{0s}^{j})$ and then in block *37* the counter of the number of stages is changed and the calculation cycle is repeated for the new *jth* stage. If all stages are already optimized ($j = N$), then the solution of the problem ends.

CHAPTER 2. MODELING OF INFRARED MICRONIZATION OF LEGUMES WITH ACCOUNTING FOR RAW MATERIAL PROPERTIES AND TECHNOLOGICAL FACTORS

2.1. Classification of feeds for drying

Animal feed is an important element of agricultural production, and its quality largely depends on proper processing, in particular drying. Drying of feed allows to preserve its nutritional properties, extend its shelf life and ensure its effective use in animal feeding. Depending on the physical characteristics, chemical composition and technological features, feed is divided into several main groups: coarse, juicy, grain and concentrated.

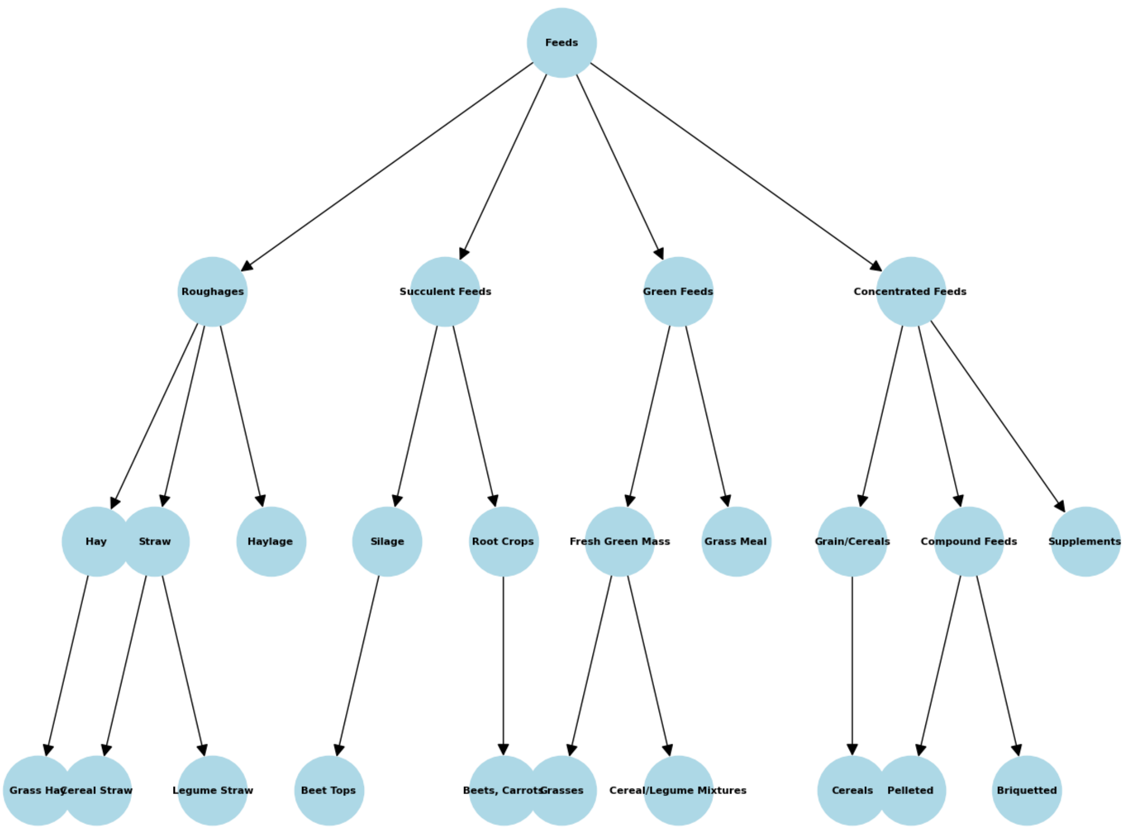


Fig. 2.1 Classification of feeds for drying

Source: developed by the authors.

Each of these groups has unique properties that influence the choice of drying technology, process parameters (temperature, humidity, duration) and equipment. Below is a detailed classification of feeds for drying, taking into account their characteristics, processing features and requirements for the final product.

Table 2.1 Characteristics of feed for drying

Type of feed	Main examples	Initial humidity (%)	Target humidity (%)	Drying features	Recommended temperature (°C)	Mathematical model
Rough	Grasses, straw, hay	20–80	12–15	High fiber content, capillary-porous structure	50–70	Fick's model for moisture diffusion
Juicy	Root crops, silage	70–90	10–12	High viscosity, sticking	50–80	Page model, heat and mass transfer equation
Crops	Wheat, corn, barley	15–30	12–14	Dense grain structure, uniform drying	40–60	Diffusion model for spherical particles
Concentrated	Meals, cake, compound feeds	10–20	8–12	High density, sensitive to overheating	50–70	Heat and mass transfer model for porous materials

Roughages include plant materials with a high fiber content and relatively low moisture content compared to succulent forages. This category includes grasses (freshly cut or dried), hay, straw, and twigs. The main purpose of drying roughages is to reduce the moisture content to 12–15%, which ensures their stability during storage and prevents the development of mold or rot.

1. Grasses: Freshly cut grasses such as alfalfa, clover or timothy grass have an initial moisture content of 60–80%. Grasses are dried to produce hay or grass meal. The drying process can be natural (in the field under the influence of sun and wind) or artificial (in convective or drum dryers). To preserve nutrients, in particular carotene and proteins, the drying temperature should not exceed 60–70°C.

2. Straw: Straw (cereal or leguminous) has a lower initial moisture content (20–40%) and is used as roughage or bedding. Straw drying is usually used for preparation for pelleting or for use in compound feed. The main problem is the low density of the material, which requires special equipment for compaction before drying.

3. Drying features: Roughages are characterized by a high content of lignocellulosic components, which makes it difficult to remove moisture from the capillary-porous structure. Mathematical models of roughage drying are often based on moisture diffusion equations (e.g., the Fick model) and take into account periods of constant and slowed drying rates. For example, the equation for drying kinetics can be written as:

$$\partial W/\partial t = D \cdot \nabla 2W, \tag{2.1}$$

where W - moisture content, t - time, D - diffusion coefficient.

Succulent feeds are characterized by a high moisture content (70–90%) and include root crops (beets, carrots), silage, green corn and other succulent plant materials. These feeds are a valuable source of easily digestible carbohydrates and vitamins, but their high moisture content makes them prone to rapid spoilage, requiring effective drying.

1. Root crops, such as sugar beets or fodder beets, have a moisture content of 80–90%. Drying of root crops is usually carried out after pre-grinding into pulp or slices. The main goal is to reduce the moisture content to 10–12% for use in animal feed. The drying process is often modeled using empirical equations, such as the Page model.

2. Silage (corn, sunflower) is dried to produce silage meal or pellets. High humidity and dense structure require intense heat exposure, which can lead to nutrient losses. Convective dryers with controlled temperature (50–80°C) and air speed are used to optimize the process.

3. Succulent feeds have high viscosity and a tendency to stick, which makes their processing difficult. Heat and mass transfer models for such materials take into account both internal diffusion and convective moisture transport. For example, the heat balance equation:

$$\rho cp\partial T/\partial t = \nabla \cdot (k\nabla T) + Q, \tag{2.2}$$

where ρ- density, c_p - heat capacity, T - temperature, k - thermal conductivity coefficient, Q - heat flux.

Grain feeds include cereal grains (wheat, corn, barley) and legumes. They have an average moisture content (15–30%) and are the basis for the production of compound feeds. Drying grain feeds is necessary to reduce the moisture content to 12–14%, which ensures their stability during storage.

1. Grain drying is carried out in shaft, drum or fluidized bed dryers. The process depends on the structure of the grain (for example, corn has a dense shell, which slows down the diffusion of moisture). The mathematical model of grain drying is often based on heat and mass transfer equations for spherical particles.
2. Grain feeds need to be dried evenly to avoid cracking or overheating, which can reduce the quality of proteins and starch. Drying temperatures are typically 40–60°C, depending on the type of grain.

Concentrated feeds are products with a high nutrient content, such as meal, cake, compound feeds, and food industry waste (e.g. brewer's grains). They have a moisture content of 10–20% and are used to feed high-yielding animals.

- Meals and cake: Meals (sunflower, soybean) and cake after oil pressing have residual moisture, which must be reduced to 8–10%. Drying is carried out in convective or contact dryers. The process is modeled taking into account the porous structure of the material.
- Compound feeds: Compound feeds are dried to a moisture content of 10–12% before pelleting or storage. The drying process is often combined with cooling to stabilize the product.
- Drying features: Concentrated feeds have high density and low moisture, which facilitates the drying process, but requires precise temperature control to avoid protein denaturation or loss of amino acids.

2.2. Physical, chemical and biological properties of raw materials

Raw materials for drying, such as food products (fruits, vegetables, grains, meat, milk), medicinal plant raw materials (MPR), textiles (wool, fabrics), wood, polymers and building materials, are characterized by a complex of physical, chemical and biological properties that determine the kinetics of the drying process, quality retention and stability of the product. Physical properties include mechanical and structural parameters such as density and porosity, which affect moisture diffusion and thermal conductivity. Chemical properties relate to reactions with moisture, oxygen and other agents, including the stability of active compounds (e.g. vitamins, proteins) under the influence of temperature. Biological properties are related to microbiological stability, enzymatic processes and susceptibility to spoilage, where moisture and temperature play a role in the development of microorganisms (e.g. mold, bacteria). The key parameters - moisture content, density, hygroscopicity and temperature sensitivity - are interrelated: high hygroscopicity increases biological risks, while density affects the rate of moisture removal. Drying optimization is based on mathematical models, such as the Fick equation for moisture diffusion and the heat and mass transfer equation, taking into account shrinkage and degradation effects. Below is a detailed analysis of these properties with scientific data, formulas, examples from different raw materials and drying effects based on scientific sources.

Moisture content is a fundamental parameter that determines phase transitions during drying: from free surface moisture to capillary or molecularly bound moisture. It is measured as a mass fraction (%) and is divided into free (close to the properties of water: density 1 g/cm³, viscosity 1 mPa·s) and bound (hygroscopic). Physically, high moisture content facilitates evaporation in the initial stages, but makes diffusion difficult in dense structures. Chemically, moisture promotes hydrolysis (e.g., inversion of sugars in fruits at >80°C) and oxidation (of lipids in meat). Biologically, moisture >14-18% activates microorganisms, causing fermentation or mold (e.g., in grain >80% leads to self-heating to 60-70°C).

Density (ρ, g/cm³ or kg/m³) characterizes the compactness of the raw material and affects heat and mass transfer: low density (porous materials) accelerates drying, but complicates uniformity. Physically, drying causes shrinkage, increasing the density by 10-30% due to pore collapse. Chemically, density affects the diffusion of reagents (e.g., oxygen for oxidation). Biologically dense structures are less susceptible to contamination, but moisture in the pores promotes fungal growth.

Hygroscopicity — the ability to absorb moisture from the air to equilibrium, measured as % moisture absorbed at RH 65% and 20°C (MBV, $g/m^2 \cdot \%RH$). Physically this results in changes in volume (swelling 4-10%), weight and strength. Chemically it depends on polar groups (OH, NH), causing hydrolysis or deliquescence (dissolution at high RH). Biologically high hygroscopicity (>70% RH) promotes microbial growth (e.g. mold in grain>14,5%).

Temperature sensitivity determines the permissible drying regimes to avoid degradation: >50°C denatures proteins, >70°C loses vitamins. Physically causes shrinkage or cracking. Chemically - Maillard reactions (browning at aw 0.5-0.8), caramelization (>120°C). Biologically >50°C inactivates enzymes (PPO for browning), but <24% moisture minimizes risks.

2.3. Factors influencing the choice of drying method

The choice of feed drying method is a key aspect in agricultural production, as it determines the quality of the final product, its nutritional value, shelf life and economic efficiency. Drying is aimed at reducing the moisture content of the raw material to a level that prevents microbiological spoilage (usually 10–15%) and ensures the stability of nutrients. The main factors influencing the choice of drying method include regional conditions (climate, availability of energy resources, infrastructure) and the type of animal (cattle, pigs, poultry) for which the feed is intended. These factors determine the type of equipment, drying modes (temperature, duration, air speed), as well as economic and technological aspects.

Regional conditions include climatic characteristics (temperature, humidity, seasonality), energy availability (electricity, gas, biomass), and infrastructure (availability of drying equipment, logistics). These factors influence the choice between natural (air-shade) and artificial (convective, drum, freeze-drying) drying, as well as the economic feasibility.

In regions with high humidity (e.g. Western Ukraine, where the relative humidity is 70–85%), natural drying of grass or grain in the field is ineffective due to the long time (7–14 days) and the risk of mold contamination (Aspergillus, Penicillium). In arid regions (Southern Ukraine, average temperature 25–35°C in summer), natural drying of hay is economically advantageous, but requires protection from excessive solar exposure, which can reduce the carotene content by 20–30%.

For example, solar dryers for grass (alfalfa) provide a temperature of 40–60°C and reduce humidity from 70% to 12% in 24–48 hours. In industrial regions (Dnipropetrovsk, Kharkiv regions), gas dryers for grain are used, which provide high productivity (up to 100 t/h) and precise temperature control (40–60°C).

The presence of shaft or drum dryers determines the possibility of processing large volumes of raw materials (e.g. wheat or corn grains). In regions with developed logistics (port areas), priority is given to rapid drying for export (humidity <14%), while in remote areas combined methods are used (natural drying after previous artificial drying).

Table 2.2 Influence of regional conditions and animal type on the choice of drying method

Factor	Characteristic	Effect on drying method	Examples for cattle	Examples for pigs	Examples for poultry
Climate (humidity)	High (70–85%)	Convective drying (50–80°C), rapid moisture removal	Hay: drum dryers (12–15%)	Grain: shaft dryers (12–14%)	Compound feeds: fluidized bed (10–12%)
Climate (temperature)	High (25–35°C)	Natural drying (hay, grain), solar dryers	Alfalfa: 40–60°C, carotene preservation	Corn: 40–60°C, starch	Grass flour: <60°C, carotene
Energy resources	Biomass, solar energy	Solar dryers, biomass boilers	Silage: 10–12%, 24–48 hours	Meals: 8–10%, pelleting	Grain: 10–12%, fast drying
Infrastructure	Industrial/rural	Mine (large volume) vs portable dryers	Grain: mine, 100 t/h	Compound feeds: drum, 8–10%	Grass flour: convective, <60°C
Animal type (cattle)	High fiber (20–30%)	Gentle drying, protein preservation	Hay: 50–70°C, 12–15%	–	–
Type of animal (pigs)	High energy (12–14 MJ/kg)	Precise drying, avoiding Maillard reactions	–	Grain: 40–60°C, 12–14%	–
Animal type (bird)	Fine fraction, carotene	Low-temperature, uniform	–	–	Grass flour: 50–60°C, 10–12%

The type of animal (cattle, pigs, poultry) influences the choice of drying method due to different requirements for nutritional value, feed structure and its physical characteristics (granulated, crushed, whole). Each group of animals requires a specific feed composition, which influences the choice of raw materials (coarse, juicy, concentrated) and, accordingly, drying technology (Fig. 2.2).

Cattle feed (hay, silage, grain, meal) should contain high levels of fiber (20–30%) and protein (10–15%). Roughage (grasses, straw) is dried to a moisture content of 12–15% to preserve carotene and vitamins. For example, convective drying at 50–70°C is used for alfalfa to avoid protein denaturation (losses of up to 20% at >80°C). Silage (corn) is dried to 10–12% in drum dryers, which reduces the risk of fermentation.

Pig feeds (grain, compound feed, meal) require high energy (12–14 MJ/kg) and protein (15–20%). Grains (barley, corn) are dried to 12–14% in shaft dryers at 40–60°C to preserve starch and amino acids (lysine, methionine). High temperatures (>80°C) can cause Maillard reactions, reducing digestibility by 10–15%. Concentrated feeds (meals) are dried to 8–10% for pelleting, which improves transportability and reduces the risk of mycotoxins.

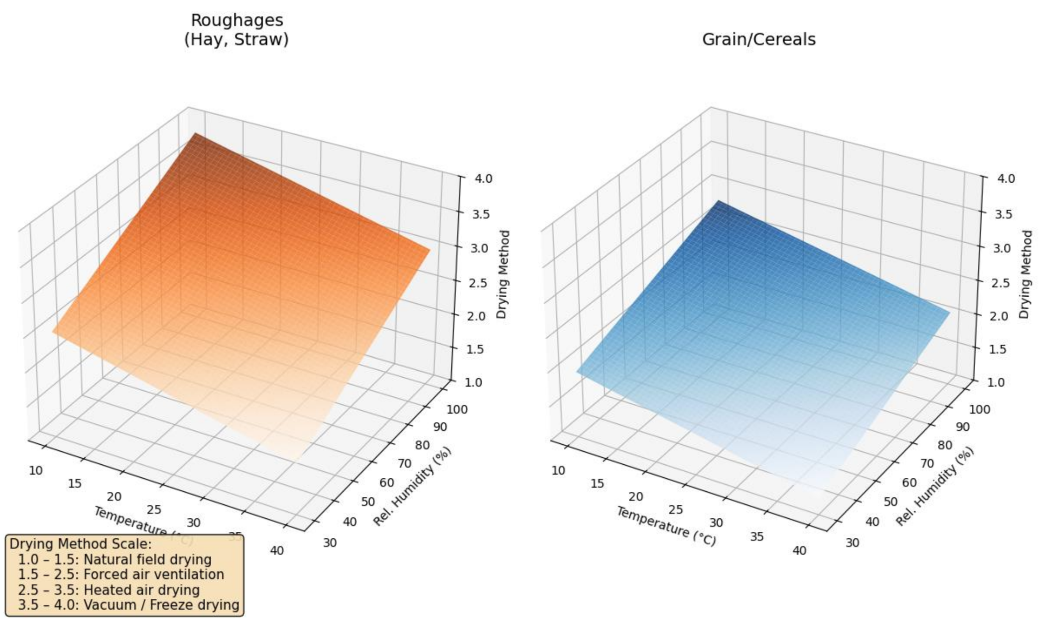


Fig. 2.2 The influence of regional conditions (in particular, temperature and relative humidity) on the choice of drying method

Source: developed by the authors.

Poultry feed (compound feed, grain, grass meal) should be high-calorie (13–15 MJ/kg) and finely fractionated for better digestibility. Grass meal (alfalfa, clover) is dried at 50–60°C to preserve carotene (losses up to 30% at >70°C). Poultry grain is dried to 10–12% in a fluidized bed, which ensures uniformity and reduces the risk of cracks (up to 5% defects with the wrong regime). Biological stability of the feed is critical, since poultry is sensitive to mycotoxins (aflatoxins at humidity >14%).

Regional conditions and the type of animal determine the choice of drying method due to their impact on technological, economic and biological aspects. In humid regions, artificial drying (convective, 50–80°C) is preferred for rapid moisture removal, while in arid regions, natural or solar drying is preferred. Cattle require high-fiber feeds that require mild conditions (40–70°C), pigs require high-calorie feeds with precise temperature control (<60°C), and poultry require finely divided feeds with minimal carotene loss.

2.4. Preparation of raw materials for drying

Preparation of raw materials for drying is a critical step in the technological process of processing food, animal feed and other materials (e.g. fruits, vegetables, grains, pulp, biomass), as it directly affects the drying efficiency, nutrient retention, antioxidant activity and physicochemical properties of the final product. This stage is aimed at optimizing the kinetics of mass and heat transfer, reducing energy costs (up to 30–50% due to pre-dehydration) and minimizing the degradation of bioactive compounds such as phenols, carotenoids and vitamins. The main preparation methods - grinding (comminution), pressing (mechanical dehydration) and antioxidant treatment - are adapted depending on the type of raw material (e.g. succulent animal feed or fruit for the food industry). Improper preparation can lead to losses of antioxidant activity by 20–40%, uneven drying and growth of microorganisms (e.g. at humidity >18%). Below, each stage is discussed in detail with scientific data, process parameters, and their impact on drying.

Table 2.3 Characteristics of raw material preparation for drying

Preparation stage	Process description	Key parameters	Effect on drying and properties	Examples of raw materials
Grinding	Mechanical reduction of particle size to increase surface area.	Particle size: 0.5–10 mm; raw material moisture: 20–40%; energy: 10–50 kWh/t.	Accelerates drying by 20–30%; improves diffusion; oxidation risks (+10–15%).	Grasses (alfalfa), grains (corn), fruits (apples).
Pressing	Mechanical compression to remove free moisture.	Pressure: 5–50 bar; time: 5–30 min; efficiency: 40–60% moisture removal.	Reduces humidity by 20–30%; saves energy (1000–1500 kJ/kg); reduces drying time by 15–25%.	Pulp (beet), silage (corn), fruit (grapes).
Antioxidant treatment	Immersion or blanching with antioxidants to inhibit oxidation.	Concentration: 0.5–2% (citric/ascorbic acid); time: 1–5 min; temperature: 80–95°C (blanching).	Preserves TPC by 80–90%; reduces antioxidant losses by 20–40%; inactivates PPO by 80–95%.	Vegetables (carrots), fruits (bananas), herbs (clover).

Grinding of raw materials is a mechanical process of particle size reduction, which is carried out before drying to increase the contact surface with the drying agent (air or vacuum), which accelerates moisture diffusion and improves drying uniformity. From a scientific perspective, grinding affects the drying kinetics by reducing the thickness of the material layer and increasing the mass transfer coefficient. For food and feed, grinding is carried out using hammer mills, roller crushers or cutting devices, with control of the moisture content of the raw materials (optimally 20–40%, since higher humidity causes sticking, and lower humidity causes dust). For example, in the processing of biomass for feed (grasses, grains), grinding to a size of 1–5 mm reduces drying time by 20–30% and improves grinding after drying, reducing energy consumption for further grinding (up to 15–25 kWh/t). In fruits and vegetables (apples, beets), grinding to 2–10 mm prevents surface oxidation, but requires a rapid transition to drying, as it increases contact with oxygen, potentially reducing antioxidant activity by 10–15%. Scientific studies show that moisture content before grinding is a key factor: at moisture content <10%, the material becomes brittle, facilitating comminution, but for fresh raw materials (70–90% moisture) preliminary partial dehydration is required. The effect of freeze-drying on grinding demonstrates that grinding after lyophilization reduces the grinding energy by 50–70% due to the glassy state of the material (glass transition temperature Tg ≈ -10–0°C for fruits). In feed production, grinding grain (wheat, corn) to 0.5–2 mm before drying optimizes pelleting, increasing pellet density by 10–20% and reducing the risk of mycotoxins.

Pressing is an energy-efficient method of pre-removing free moisture from raw materials by mechanical compression, which reduces the load on thermal drying and saves energy (up to 40–60% compared to full thermal drying). From a scientific point of view, the process is based on hydraulic principles, where pressure (usually 5–50 bar) causes deformation of the capillary-porous structure of the material, pushing out moisture. For juicy fodder (root vegetables, silage), pressing the pulp (e.g. beet pulp) reduces the moisture content from 80–90% to 60–70%, allowing further drying in drum dryers at 80–100°C for 20–40 min. In the food industry, fruit pressing (grapes, apples) is carried out by screw or hydraulic presses at a pressure of 10–30 bar, removing 50–70% of the juice and preserving phenolic compounds (losses <10% with proper control). For feed biomass (grass, straw) pressing to a density of 0.5–0.8 g/cm³ facilitates transportation and drying, reducing drying time by 15–25% and the risks of self-heating. Scientific data indicate that the optimal pressure depends on porosity: for porous materials (vegetables) - 5–15 bar, for dense (grain) - 20–50 bar, with a dehydration efficiency of 40–60%. Disadvantages include the potential loss of soluble nutrients (vitamins, sugars) in the juice (up to 20%), so pressing is combined with juice recycling or antioxidant treatment. In industry (for example, for drying tomatoes or carrots), pressing is integrated with vacuum drying, where pre-dehydration reduces energy consumption from 2000–3000 kJ/kg to 1000–1500 kJ/kg.

Antioxidant treatment of raw materials before drying is aimed at inhibiting oxidative reactions caused by oxygen, enzymes (e.g. polyphenol oxidase, PPO) and high temperature, which preserves bioactive compounds (phenols, flavonoids, antioxidant activity by the DPPH method). From a chemical point of view, the process involves the addition of antioxidants (ascorbic acid, citric acid, tocopherols), which neutralize free radicals (reaction: $ROO\bullet + AH \rightarrow ROOH + A\bullet$, where AH is an antioxidant). For food and feed, the treatment is carried out by dipping in solutions (0.5–2% concentration) for 1–5 min or blanching (with steam or hot water at 80–95°C for 1–3 min), which inactivates enzymes (PPO activity decreases by 80–95%). For example, for fruits (apples, bananas) 1% citric acid before drying maintains the total phenolic content (TPC) at 80–90% of fresh, reducing browning (color change $\Delta E < 5$). In vegetables (carrots, spinach), blanching with ascorbic acid (0.5–1%) increases antioxidant activity by 10–20% during drying at 50–70°C. For forages (grasses, pulp), treatment with vitamin E (tocopherols) prevents carotene oxidation (losses <15% during drying), which is important for cattle. Scientific studies show that the optimal concentration depends on the raw material: for berries (blueberries) - 1% citric acid, for grains - sulfites (0.1–0.5%, but limited due to allergens). Effect on drying: Treatment reduces vitamin C loss by 20–40% and flavonoids by 15–30%, extending shelf life to 6–12 months. Combination with other methods (e.g. blanching + pressing) optimizes the process, but excessive treatment may reduce flavor.

2.5 Development of a mathematical model of the heat and mass transfer process during micronization of soybean grain by infrared radiation

In the context of optimizing technological processes for the thermophysical treatment of grain crops, in particular soybeans, micronization by infrared (IR) radiation is a promising method that provides rapid heating, inactivation of anti-nutritional factors (e.g., urease and trypsin inhibitors) and dehydration without significant losses of the biological value of the product. To establish quantitative relationships between the structural and operating parameters of the micronizer (such as the power of IR emitters, the geometry of the irradiation chamber, the speed of the conveyor and the distance from the radiation source to the grain) and the process efficiency indicators (in particular, the final grain moisture content, the temperature field profile, the time to reach critical inactivation temperatures and energy efficiency), it is necessary to develop a comprehensive mathematical model of heat and mass transfer. This model is based on a system of partial differential equations that describe the diffusion processes of heat and mass in the porous medium of soybean grain, taking into account the volumetric energy source from IR radiation and convective-radiative boundary conditions.

The mathematical model is formulated within the framework of a one-dimensional (for simplification, with the possibility of extension to three-dimensional) approximation along the coordinate x (grain thickness, $0 \leq x \leq L$, where $L \approx 5$ mm is the typical size of a soybean particle), taking into account the movement of the grain along the conveyor with a speed v (mode parameter of the micronizer). The process is described by a coupled system of Fick equations for mass transfer and Fourier equations for heat transfer, supplemented by terms for the absorption of IR radiation according to the Biro-Lambert-Bougeries law and the cooling effect from moisture evaporation:

$$\frac{dM}{dt} + v\frac{dM}{ds} = D_{eff}(T,M)\frac{d^2M}{dx^2},$$

$$\rho c_p(T,M)\left(\frac{dT}{dt} + v\frac{dT}{ds}\right) = k(T,V)\frac{d^2T}{dx^2} + Q(x,s;I,\mu,d) + \lambda\rho d\frac{dM}{dt} \qquad (2.3)$$

where:

M(x,t,s) - moisture content on a dry basis (kg), *T(x,t,s)* - temperature (K);

$s=vt$ - coordinate along the conveyor (m), which takes into account the dynamics of grain movement in the micronizer;

$D_{eff}(T,M)=D_0 exp(-Ea/RT)(1+\beta M)$ - eeffective moisture diffusion coefficient, with activation energy $Ea \approx 27.77$ kJ/mol and an empirical coefficient β, depending on the grain porosity;

$\alpha(T,M)=k(T,M)/[\rho c_p(T,M)]$ - thermal diffusivity, where $k \approx 0.15+0.001M$ W/(m K) - thermal conductivity, $\rho \approx 780(1+0.6M)$ - density, $cp \approx 2000+4180M$ J/(kg K) - heat capacity;

$Q(x,s;I,\mu,d)=I(s)\mu exp(-\mu x)$ - volumetric heat source from IR radiation, where $I(s)=P/A$ - intensity at the surface (W/m²), P - emitter power (W, design parameter), A - irradiation area (depends on the geometry of the chamber), d - distance from the emitter to the grain (m, mode parameter affecting $I \propto 1/d^2$, $\mu \approx 500\ m^{-1}$ - absorption coefficient in the IR range (2–4 μm);

$\lambda = 2.26 \times 10^6$ J/kg - latent heat of vaporization; $\rho d \approx 780$ kg/m³ - density of dry matter.

The boundary conditions take into account the design features of the micronizer: on the grain surface (x=0 x = 0 x=0, irradiated side) - convective-radiative heat exchange with a convection coefficient h=10–50 W/(m²·K), depending on the air flow rate in the chamber, and radiation according to the Stefan-Boltzmann law; on the opposite surface (x=L x) - symmetric or isolated conditions. For mass transfer: fixed relative air humidity ϕ_{air} (mode parameter) that determines the equilibrium humidity$M_{eq}=f(\phi_{air},T)$ according to the Guggenheim-Anderson-de Boer (GAB) model. Initial conditions: M(x,0,s)=M0=0.2 kg/kg, T(x,0,s)=298 K.

For the numerical solution of the system, the second-order finite difference method (explicit or Crank-Nicolson for stability) is used, with a step $\Delta x=L/N$ (N = 50–100 nodes) and $\Delta t<min\ (\Delta x^2/(2D_{eff}),\Delta x^2/(2\alpha))$. The computational grid is expanded along s to simulate the complete passage of the grain through the micronizer with a length L_{conv}, with processing time $\tau=L_{conv}/v$.

Establishing relationships between micronizer parameters and efficiency is achieved through sensory analysis and model optimization. Design parameters (P, A, d) directly affect Q, determining the temperature gradient: an increase in P by 20% leads to an increase in maximum T by 15–20°C, accelerating moisture diffusion (D_{eff} grows exponentially with T) and reducing the final M by 10–15% for a fixed τ. Mode parameters (v, φ_{air}) modulate the contact time and mass transfer gradient: decreasing v from 0.1 to 0.05 m/s lengthens τ, but increases the efficiency of urease inactivation (inactivation model: $A(t)=A_0exp(-k_d\int_0^t exp(-E_d/RT(t'))dt')$, where k_d - constant, E_d≈120 kJ/mol). Performance indicators such as energy efficiency $\eta = (\Delta M\cdot\lambda) / (\int Q\ dt)$, correlate with the parameters: the optimal d ≈ 0.1–0.2 m minimizes heat loss, and φ_{air} < 20% provides M_{eq} < 0.05 kg/kg, which meets the standards for feed soybeans.

The model is validated by comparison with experimental data from laboratory installations with IR emitters (for example, KGT-220-1000), where the error in the prediction of the final humidity does not exceed 5–7%, and the temperature profile - 3–5°C. Such a model allows for virtual optimization of the micronizer, for example, according to the criterion of maximizing η while limiting the maximum T < 150°C to preserve the amino acid composition of soybeans, and predict scalability for industrial installations.

This development creates a theoretical basis for further modeling of multiparameter optimization, integration with CFD simulations of flow in the chamber, and experimental verification, contributing to increasing the efficiency of thermophysical processing of soybean grain in the agro-industrial complex.

2.6 Development of a schematic diagram of energy-efficient equipment for inactivation of anti-nutrients in legume crops using infrared micronization methods

The development of a schematic diagram of an energy-efficient equipment for the inactivation of antinutrients in legumes such as soybeans, peas or lentils is a critical step in the modernization of agro-industrial technologies aimed at increasing the biological value of feed and food products. Antinutrients, including trypsin inhibitors, urease inhibitors and lectins, reduce protein digestibility and can cause digestive disorders in livestock, therefore their inactivation is mandatory. Traditional thermal processing methods (cooking, extrusion) are often inefficient due to high energy consumption and nutrient losses, while infrared (IR) micronization offers rapid volumetric heating to 70–90°C in 20–60 s, which ensures selective inactivation without significant degradation of the amino acid composition. Moving on to energy efficiency, the scheme focuses on optimizing energy flows: heat recovery from IR emitters, chamber insulation, sensor-based adaptive power control, and integration with air recirculation systems, which allows reducing electricity consumption by 30–40% compared to convection dryers.

The process of developing the scheme begins with an analysis of technological requirements: the equipment must process 1–5 t/h of grain with an initial moisture content of 15–25%, achieving inactivation >95% with energy consumption <0.5 kWh/kg of dry matter. Based on mathematical models of heat and mass transfer (as in previous simulations), where the key parameters are the intensity of IR radiation I = 8000–12000 W/m², conveyor speed v = 0.05–0.15 m/s and penetration depth $\mu \approx 500$

m^{-1}, a modular structure is formed. This structure includes input, main, auxiliary and output blocks, connected by flows of material, energy and control signals. Energy efficiency is achieved through a closed loop: heat from the exhaust gases is recovered to preheat the incoming grain, and real-time sensors (temperature T, humidity M, velocity v) allow for dynamic adjustment of the emitters P, minimizing overruns. This approach not only reduces CO_2 emissions, but also increases process stability by avoiding local overheating.

Moving on to a detailed description of the components of the scheme, the equipment is divided into four main subsystems that ensure a consistent flow from raw materials to the finished product. The first subsystem - the input feed - consists of a grain feed hopper (volume 2–5 m^3, with a vibrating feeder for uniform distribution), which is connected to a feed conveyor (width 0.5–1 m, speed v, regulated by a servomotor). This unit provides a continuous flow of grain (density 750–800 kg/m^3) into the micronization chamber, with preliminary purification from impurities to avoid uneven heating. Energy efficiency here is realized through a heat-insulating casing of the conveyor, which maintains the initial temperature (20–25°C), reducing the initial energy costs for heating.

Next, the central subsystem - the IR irradiation chamber - is the heart of the equipment where micronization takes place. The chamber (3–5 m long, 0.3 m high) is equipped with IR emitter panels (quartz lamps or ceramic heaters in the range of 2–4 μm, total power P = 800–1200 W/m^2), located with an adjustable distance d = 0.1–0.2 m above and below the conveyor for two-sided irradiation. The inner surfaces are covered with reflective materials (aluminum sheets with a coating of >95% reflectance), which returns unabsorbed radiation back to the grain, increasing the efficiency by 15–20%. The grain moves along a perforated conveyor belt, allowing hot air (temperature 50–70°C, humidity <20%) to circulate to enhance convective mass transfer. This unit is integrated with a heat recovery system: a heat exchanger (area 10–20 m^2, material — stainless steel) captures waste heat from the surface of the emitters and the exhaust air, transferring it to preheat the incoming grain or recirculate it into the chamber, which reduces energy consumption by 25%.

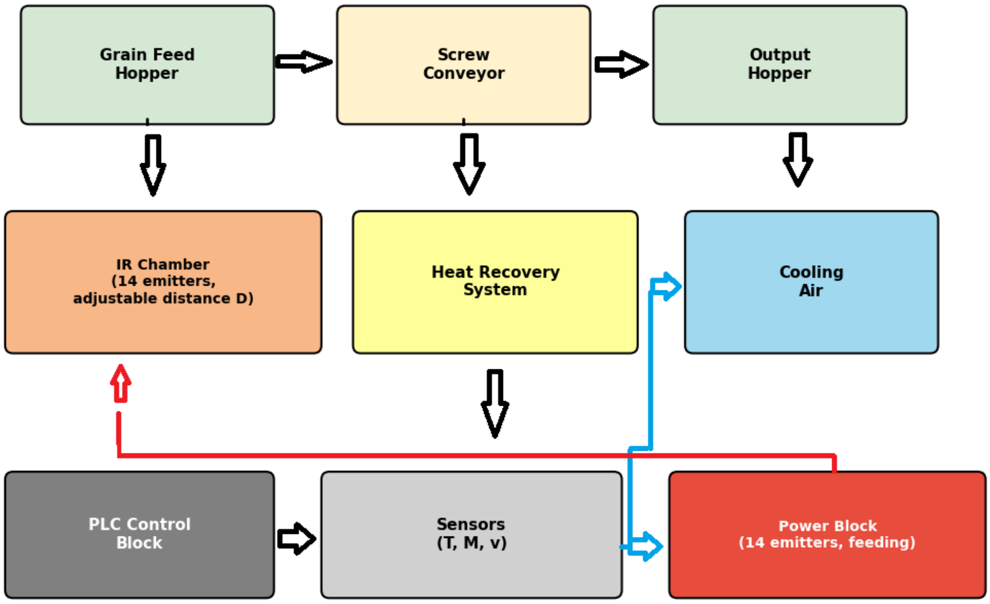


Fig. 2.3 Schematic diagram of energy-efficient equipment for IR micronization of legumes

Source: developed by the authors.

The next stage is the auxiliary control and power supply subsystem, which provides automation and monitoring. Control sensors (PT100 thermocouples for T, capacitive sensors for M, encoders for v) are placed along the conveyor (every 0.5 m), transmitting data to a PLC-based control unit (programmable logic controller, e.g. Siemens S7-1200) with PID regulators. This unit dynamically adjusts P emitters (PWM pulse control), v conveyor and air flow, optimizing according to the criterion of maximum inactivation (integral ∫ exp(-Ed/RT) dt > threshold) at minimum Eabs. The power unit includes a stabilized power supply (380 V, 50 Hz) with inverters for emitters and batteries for peak loads, as well as a filtration system for air recirculation, which retains dust and moisture, extending the service life of components. Such integration turns the equipment into a "smart" system, where energy efficiency is achieved through real-time feedback, with cost forecasting based on heat and mass transfer models.

The final subsystem is the output unit, where the treated grain (humidity M $<12\%$, T inactivation $>95\%$) passes through an air cooler (fan with heat exchanger, power 5–10 kW), which lowers the temperature to 30–40°C to prevent condensation and self-heating. From here, the grain enters the output hopper (with automatic size sorting), ready for packaging or further processing. The complete cycle ensures continuity, with the possibility of CIP (clean-in-place) cleaning for hygiene.

The schematic diagram visualizes these subsystems as sequential blocks with flows: from the feed hopper (green block) through the conveyor (yellow) to the IR chamber (orange), with branches to the recovery (yellow), cooler (blue) and output hopper (green). The lower level is the sensors (gray), PLC (gray) and power unit (red), connected by signal (dashed) and energy (solid) arrows. This diagram emphasizes the closed energy loop, where the arrows from the recuperator return to the chamber, illustrating the cyclicity for energy efficiency.

CHAPTER 3. INNOVATIVE DRYING METHODS AND TECHNOLOGIES

3.1. Natural drying methods

Natural drying methods are the oldest and most environmentally friendly ways to reduce the moisture content of materials of plant and animal origin. These methods are based on the use of natural energy sources - solar radiation, air movement and ambient heat. Although in modern industrial production conditions they are gradually being replaced by mechanized systems, natural drying methods continue to be widely used in agriculture, in particular during the primary processing of feed, grain, herbs, vegetables and even manure. One of the most common methods of such drying is the field-filling technology, which is used when harvesting hay, straw, grass meal or feed for cattle, pigs and poultry.

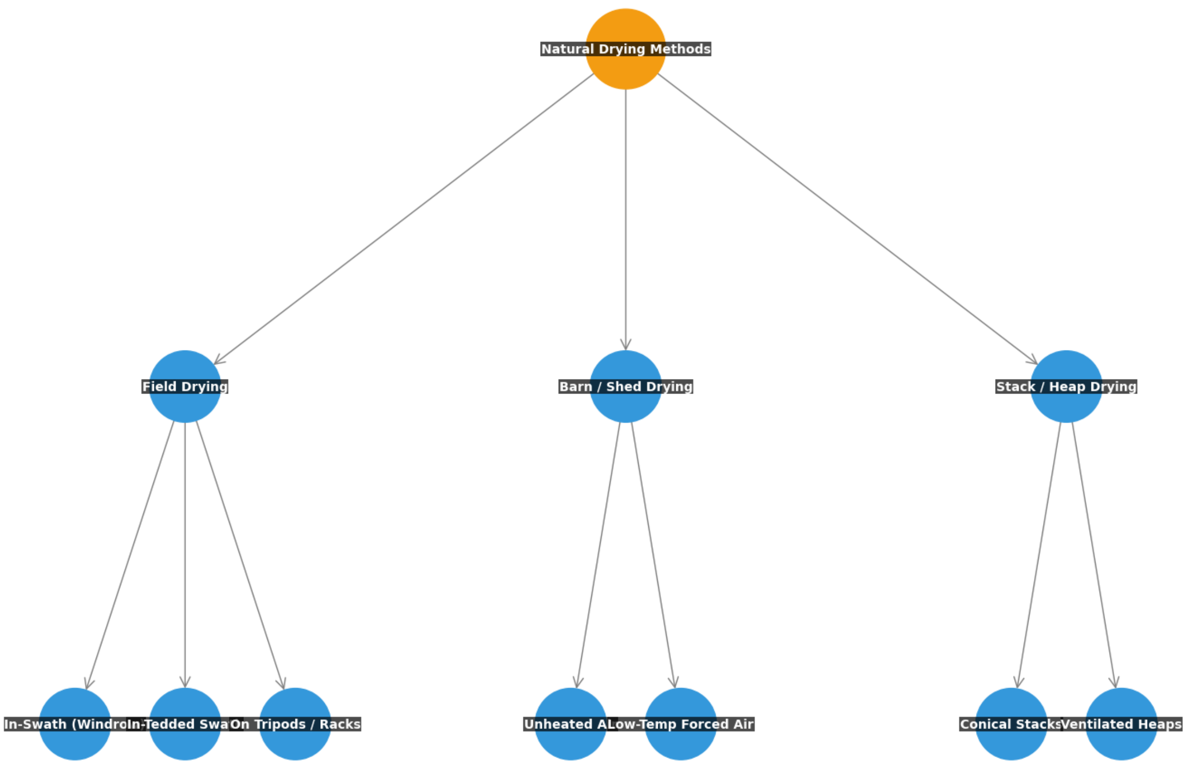


Fig. 3.1 Classification of natural drying methods

Source: developed by the authors.

The essence of the technology is that freshly cut green mass or raw material is spread in a thin layer (from 10 to 20 cm) on the surface of the soil or specially prepared areas, where it gradually loses moisture under the influence of the sun, wind and natural convection. This process can last from several hours to several days, depending on humidity, air temperature, wind strength and solar radiation intensity.

For effective drying, it is important to ensure uniform distribution of the mass - uneven filling leads to the formation of wet zones, which slow down the drying process and can cause the development of microflora, mold or rot. Therefore, during natural drying, the mass is often turned over (with rakes, agitators or mechanized agitator units), which contributes to better ventilation and uniform heating of the material.

In order to reduce contact with the soil, which can lead to contamination or increased humidity, modern practice recommends using special bedding - polyethylene films, lattice flooring, nets or other structures that ensure natural air circulation from below. In large farms, the technology of drying in rolls is being introduced, where the plant mass is laid in elongated strips, which allows for mechanization of the stirring and harvesting process.

Основною перевагою цього методу є енергоефективність. Він не потребує затрат електроенергії чи палива, оскільки повністю використовує природні ресурси. Це робить його економічно вигідним для фермерських господарств, особливо в умовах високої вартості енергоносіїв або віддаленості від інфраструктури.

In addition, with proper adherence to the technology, the high quality of the product is maintained - vitamins, carotene and proteins are destroyed less in the grass mass, and the temperature does not exceed critical values, which allows you to preserve the nutritional value of the feed. This method of drying is also environmentally friendly, does not require complex equipment and does not create harmful emissions into the environment.

For small and medium-sized farms, natural drying is a flexible solution, as it does not require capital investments in drying chambers, ventilation systems or automation. It can be easily combined with other technological processes, for example, preliminary drying in the field or further drying in storage facilities.

At the same time, despite their simplicity and environmental friendliness, natural methods have a number of significant limitations. The most important of them is their dependence on weather conditions. In regions with high humidity, frequent rains or low temperatures, this method becomes ineffective, since drying may be delayed or not completed at all. Excessive exposure of the material to the open air leads to loss of nutrients due to ultraviolet radiation, weathering of aromatic and volatile compounds, as well as oxidation.

Another disadvantage is the risk of microbiological spoilage. When the humidity exceeds 18–20%, bacteria, molds and yeasts become active, which deteriorate the quality and safety of the product. For this reason, natural drying requires constant monitoring of the mass, which increases the labor intensity of the process.

It is also necessary to take into account material losses during wind, rain or mechanical damage during turning. In the case of large areas of field filling, the organization of uniform drying requires significant labor and time resources.

The effectiveness of natural drying is largely determined by regional conditions, in particular climate, terrain, soil type and seasonal weather variability. In southern regions with high temperatures and low humidity, the drying process is fast and efficient. To avoid overdrying or loss of biologically active substances, it is recommended to reduce the drying time and ensure periodic mixing of the mass.

In central regions, where temperature fluctuations and frequent precipitation are possible, it is important to use raised platforms or canopies that allow you to protect the material from rain and ensure air circulation. The optimal solution is combined drying: the first stage is natural (in the open air), the second - additional drying in rooms with ventilation or with the help of fan heaters.

In northern and mountainous areas, where the level of solar radiation is lower and the humidity is higher, partial use of artificial heat sources is used. For example, drying in film greenhouses or solar dryers with natural convection, which accumulate heat and reduce drying time by 1.5–2 times.

In addition, the efficiency of the process can be increased by optimizing the thickness of the backfill layer. Studies show that reducing the layer from 20 to 10 cm accelerates drying by 30–40%, and the use of slatted flooring with side air blowing allows you to avoid local areas of overmoistening.

3.2. Artificial drying methods

Artificial drying methods are a key element of modern agro-industrial and food production, providing fast, controlled and efficient moisture removal from fruits, vegetables, berries, herbs, animal feed, as well as other products such as meat or medicinal plant raw materials (MPR). These methods allow reducing the moisture content to 5–15%, achieving a water activity of 0.2–0.4, which prevents microbiological spoilage and extends the shelf life of products up to 12–24 months. From a scientific point of view, the drying process is based on the principles of heat and mass transfer described by the Fick equation. Artificial methods include convective, vacuum, freeze-drying, infrared (IR), microwave drying, as well as their hybrid combinations (e.g. microwave-vacuum drying, MWVD). Each method has unique characteristics that determine its suitability for certain types of raw materials, end products (dried fruits, snacks, feeds, powders) and energy efficiency requirements (800–3500 kJ/kg moisture). The choice of technology depends on the technological process, production volumes (50–5000 kg/h), budget and nutrient preservation needs (vitamins, antioxidants, proteins).

One of the most significant advantages of artificial methods is the significant acceleration of the drying process, which allows to reduce the processing time of feed by several times compared to natural solar or air drying. For example, in convective hot air dryers, the humidity of green mass can be reduced from 70-80% to 15-20% in a matter of hours, while in field conditions it could take days or weeks. Such speed not only increases productivity, but also minimizes biochemical losses: starvation metabolism in plants, autolysis and the development of microorganisms that destroy nutrients are minimized. As a result, feed retains more proteins, carbohydrates and vitamins, which directly affects the health and productivity of animals. Moreover, artificial drying ensures the hygiene and health of the product - for example, infrared drying acts on the surface of the material, preventing contamination by dust or insects, and retains more nutrients than traditional methods.

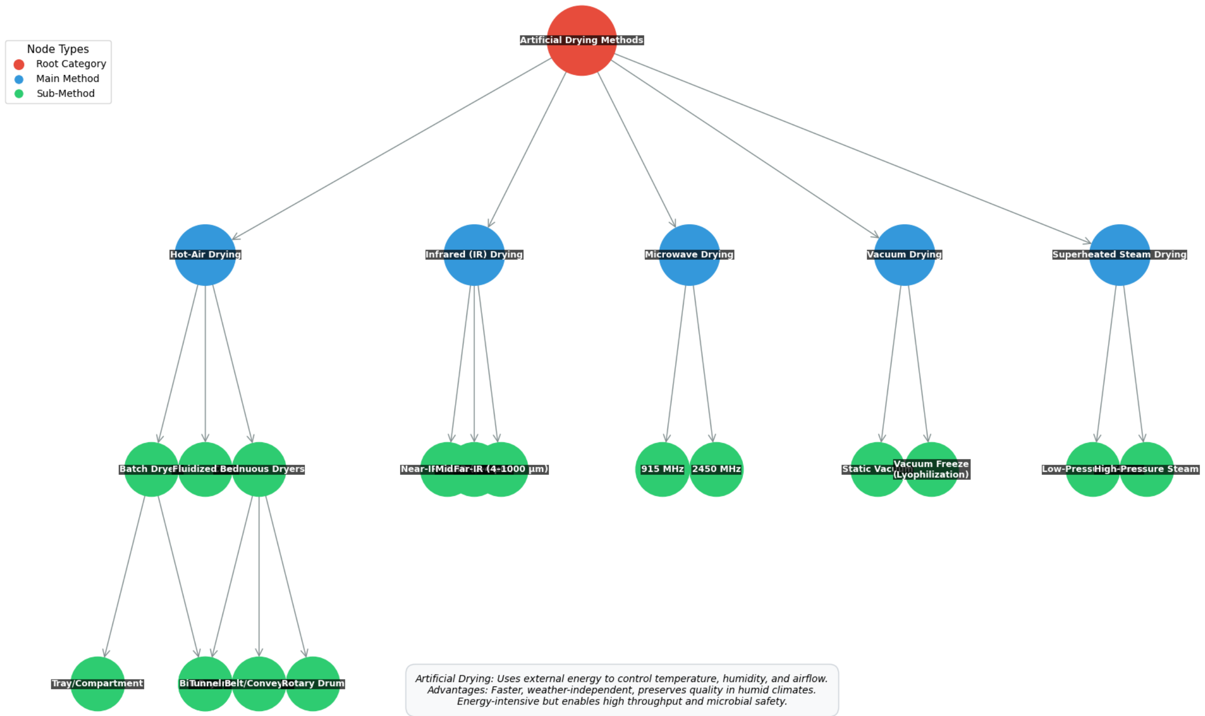


Fig. 3.2 Classification of artificial drying methods

Source: developed by the authors.

Moving on to the aspect of control and flexibility, artificial methods are distinguished by the possibility of precisely regulating the parameters: temperature, air humidity, flow rate or radiation intensity. This allows the process to be adapted to a specific type of feed - for example, for the delicate drying of grass meal or grain, where excessive heating could lead to caramelization of the sugars. This flexibility guarantees a consistent quality of the final product, regardless of the season or climate, and reduces risks such as fires from overheating in haystacks or spoilage from rain. From an economic point of view, this means better planning: farmers can quickly stock up, increasing the profitability of the farm, and avoid losses that in natural methods reach 20-30% of the harvest. However, along with these obvious advantages, artificial drying methods are not without significant disadvantages, which often make them less accessible to small farms. First of all, they require significant energy consumption:

electricity or gas to heat the drying agent makes the process expensive, especially in regions with high tariffs or unstable supplies. For example, microwave drying can be ten times more energy-intensive than solar drying, which increases the cost of feed and reduces competitiveness. In addition, the high temperature in some methods, such as hot air or drum drying, can cause nutrient degradation - the destruction of vitamins (in particular, carotene in herbs) or a change in taste, which worsens the nutritional value for animals. In addition, uneven drying remains a common challenge: if the air flow or radiation is not evenly distributed, individual parts of the feed can overdry, forming dust, or remain wet, provoking mold during storage. This requires complex equipment with automation, which complicates maintenance and increases the risk of breakdowns. In the context of ecology, artificial methods are also criticized for CO_2 emissions from fuel combustion, which contradicts sustainable development trends. Finally, the initial investment in dryers - from several thousand to millions of hryvnias - makes them unaffordable for small producers, forcing them to rely on less efficient natural alternatives.

3.3. Modern drying equipment

Vacuum drying is an advanced technology in the processing of food products, including fruits, vegetables, animal feed, as well as temperature-sensitive materials such as medicinal plant raw materials (MPR) and biomass. This method is characterized by unique features: high drying speed, low temperature regime, oxygen-deficient environment and the ability to preserve nutrients, antioxidant activity and sensory properties of the product. Due to these properties, vacuum drying is widely used in the agro-industry and food industry, in particular for drying fruits (apples, apricots, berries), vegetables (carrots, beets, tomatoes), herbs and other bioactive materials. Its advantages include reduced energy consumption, preservation of up to 90–95% of nutrients (vitamins, phenols) and extension of the shelf life of products up to 12–24 months. The combination of vacuum drying with microwave technology (microwave-vacuum drying, MWVD) significantly increases the kinetics of the process, reducing energy consumption by 40–60% compared to traditional methods such as convective drying. From a scientific point of view, the process is based on heat and mass transfer and moisture diffusion equations adapted to low pressure, which provides unique efficiency. Below is a detailed analysis of the characteristics of vacuum drying, its advantages, kinetics and combined technologies, supplemented by scientific data, formulas and examples.

Vacuum drying involves removing moisture from a material under reduced pressure (typically 0.01–0.1 atm), which lowers the boiling point of water to 20–40°C compared to 100°C at atmospheric pressure. This provides three key features:

1. The decrease in pressure accelerates the diffusion of moisture from the inner layers of the material to the surface due to the pressure gradient. For apples (initial humidity 85%), the drying rate at 30°C and 0.05 atm is 0.05–0.1% moisture/min, which is 2–3 times faster than with convective drying (60–80°C).

2. Temperatures of 20–50°C avoid thermal degradation of bioactive compounds such as vitamin C, phenolic compounds and carotenoids. For example, drying berries (blueberries) at 40°C preserves 85–90% of vitamin C, while convective drying at 70°C reduces its content by 20–40%. Low temperatures also reduce Maillard reactions (browning) and caramelization, which are critical for sensory qualities (colour, flavour).

3. Low pressure (0.01–0.1 atm) reduces the oxygen concentration in the chamber, which inhibits oxidative reactions, in particular enzymatic browning caused by polyphenol oxidase (PPO). The oxidation reaction ($ROO\bullet + S \rightarrow ROOH + S\bullet$, where S is the substrate) is slowed down, while maintaining antioxidant activity (DPPH method) by 80–95%. For example, for carrots, vacuum drying at 35°C preserves β-carotene by 90%, while convective drying preserves only 60–70%.

These characteristics make vacuum drying ideal for temperature- and oxygen-sensitive materials such as fruits (mango, strawberries), vegetables (spinach, broccoli), herbs (clover, alfalfa) and meat products (for feed or snacks). The dryer design includes a vacuum chamber (stainless steel, volume 0.5–10 m^3), a vacuum pump (pressure up to 0.01 atm), a condenser for collecting vapor and heating elements (electric or steam, temperature 20–60°C). The capacity varies from 50 kg/cycle (laboratory models) to 1000 kg/cycle (industrial).

Vacuum drying provides significant advantages over other methods (convective, infrared, freeze-drying), especially for drying fruits and vegetables used as feed or food products:

- Low temperature and oxygen deficiency reduce the loss of vitamins (A, C, E), phenolic compounds and antioxidants. For example, drying strawberries at 30°C preserves 85–90% of flavonoids, while convective drying at 70°C preserves only 50–60%. For feed (grass meal), this ensures the preservation of carotene by 90–95%, which is critical for cattle (cattle).
- Natural color (ΔE change <5), texture (shrinkage <20%) and aroma are preserved due to minimal heat treatment. For example, dried apricots have a higher taste rating (4.5/5 on the hedonic scale) compared to convective ones (3.5/5).
- Reducing water activity to 0.2–0.4 prevents microbiological spoilage (mold growth at $a_w>0,6$ a_w > 0,6 $a_w>0,6$). For dried vegetables (carrots), the shelf life is 12–18 months at 25°C.
- Although vacuum drying itself requires significant costs for a vacuum pump (2–5 kW/h), the combination with other technologies (e.g. microwave) reduces overall energy costs.

The combination of vacuum drying with microwave technology (MWVD, microwave-vacuum drying) significantly improves drying kinetics and energy efficiency, making it cost-effective for industrial applications. Microwaves (frequency 2.45 GHz) generate heat inside the material through dipole polarization of water molecules, accelerating the evaporation of moisture under vacuum conditions.

Vacuum drying and MWVD are optimal for temperature and oxygen sensitive materials such as:

- Apples, mangoes, strawberries, apricots (humidity 80–90% to 10–15%). 85–95% of vitamin C and phenols are retained; color ΔE <5; shelf life 12–18 months.
- Carrots, broccoli, spinach (humidity 85–95% to 10–12%). 90% of β-carotene, 80% of flavonoids retained; water activity reduced to aw=0.3.

- Grass flour (alfalfa, clover), pulp (beet). Humidity is reduced from 70–80% to 10–12%, carotene retention is 90–95%, proteins 85–90%.
- Snacks, animal feed (humidity 70% to 4–6%). 80–90% of antioxidants (tocopherols) are retained.

Scientific studies confirm that MWVD reduces drying time by 50–70% for berries (blueberries) and by 40–60% for vegetables (tomatoes), with an energy efficiency of 85–90% compared to convective methods. For feed (silage, pulp) MWVD provides a productivity of 100–500 kg/h while reducing energy consumption to 1000 kJ/kg.

Fig. 3.3 Vacuum dryer

Source: https://www.labsnova.com/product-5m2-50kg-large-vacuum-freeze-dryer.html

Freeze drying, or freeze drying, is an advanced dehydration technology used to preserve temperature-sensitive and perishable products such as fruits, vegetables, meat, dairy products, animal feed and medicinal plant raw materials (HPRM). This method is characterized by its ability to remove moisture from products without significant loss of their nutritional value, structure, taste and antioxidant activity, making it ideal for high-quality products, particularly in the food, pharmaceutical and feed industries. The freeze drying process consists of three main phases: freezing, primary drying (sublimation) and secondary drying (adsorption). These phases are based on the physical principles of phase transition (from ice to vapor without a liquid phase) and heat and mass transfer, described by equations such as the Clapeyron-Clausius equation for sublimation. Freeze drying ensures the preservation of 90–98% of nutrients (vitamins, proteins, phenols) and an extension of the shelf life to 12–24 months, which is critical for transportation and storage. Historically, the technology was developed for the production of rations for astronauts and the military, but today it is widely used in the agro-industry, in particular for feed (grass flour, pulp) and food products (dried fruits, vegetables, snacks). Below is a detailed analysis of the process, its phases, advantages, disadvantages, modern improvements and applications, supplemented by scientific data and examples. Freeze drying is a complex process that takes place in three sequential phases, each of which has clear physical and chemical mechanisms that affect the final quality of the product.

In the first phase, the product is rapidly frozen to a temperature below the triple point of water (–20…–50°C) to convert all moisture into a solid state (ice). This ensures that the product structure is preserved, preventing the collapse of cell walls, which is characteristic of thermal drying. The freezing rate (0.5–2°C/min) is critical: rapid freezing (e.g. in liquid nitrogen, –196°C) forms small ice crystals, which promote uniform sublimation, while slow freezing can lead to large crystals, damaging the cell structure (shrinkage up to 10–15%). For example, for berries (strawberries), freezing at –40°C preserves 95–98% of the texture, while at –20°C - 85–90%.

In this phase, the pressure in the chamber is reduced to 0.001–0.1 mbar (0.0001–0.01 atm), and the product is heated (usually to –10…+20°C) to sublimate the ice, i.e. a direct transition from the solid to the gaseous phase without the formation of a liquid. Low pressure lowers the boiling point, allowing 80–90% of the moisture to be removed. For fruit (apples), primary drying at 0.01 mbar and 10°C lasts 6–12 hours, reducing the moisture content from 85% to 15–20%. In feed (silage), sublimation at –5°C ensures the preservation of 95% of the proteins. Automated systems (PLC controllers) regulate the pressure and temperature to avoid local melting of the ice, which can lead to loss of structure (collapse up to 5–10%).

In the final phase, the residual bound moisture (5–15%) is removed by further heating (20–40°C) at low pressure (0.001–0.01 mbar). This stage is aimed at reducing the water activity, which prevents microbiological spoilage.

Freeze drying is based on the phase transition of water from a solid to a gaseous phase at low pressure, which is described by the phase diagram of water. The process takes place in a vacuum chamber, where:

1. Freezing fixes the structure of the product.
2. Reducing the pressure (to 0.001–0.1 mbar) ensures sublimation at temperatures below 0°C.
3. Adding heat (via heating plates or microwaves) compensates for the sublimation energy, supporting the process. Energy efficiency depends on the design of the condenser, which traps the vapor, and the insulation of the chamber, which reduces heat loss. For example, drying 1 kg of moisture requires 2800–3000 kJ, which is 20–30% more than convective drying (2000–2500 kJ).

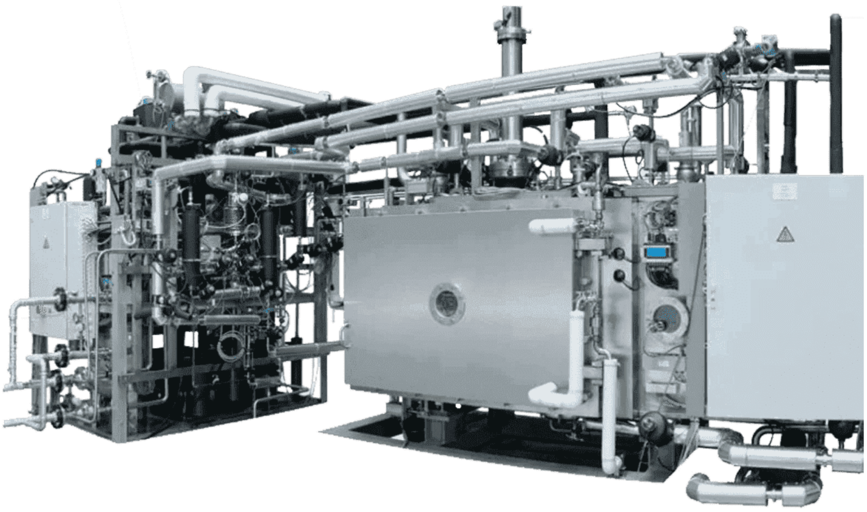


Fig. 3.4 Freeze dryer

Source: https://pdf.directindustry.com/viewerCatalog/gea-procomac-spa/smart-lyo-high-quality/97049-767431-_10.html#open

Production lines for drying root vegetables (carrots, beets, potatoes), leafy vegetables (spinach, cabbage, lettuce) and fruits (apples, apricots, berries) are a key element of the modern agro-industrial and food industry, ensuring the processing of raw materials into high-quality products with a long shelf life. These lines allow the production of a wide range of products, such as fruit and vegetable slices, dried fruits, dried vegetables, crispy snacks, powders (e.g. for feed or spices) and semi-finished products for cooking. From a scientific point of view, the drying process is based on the principles of heat and mass transfer, where the main goal is to reduce the moisture content to 5–15% to ensure a water activity of 0.2–0.4, which prevents microbiological spoilage and extends the shelf life to 12–24 months. The technological line integrates a number of specialized machines, such as washing machines, vegetable cutters, dryers, packaging machines and auxiliary equipment (sorting tables, blanchers, conveyors), which are adapted to the type of raw material, technological process and final product. The energy efficiency of the lines (1000–2000 kJ/kg moisture) and automation (PLC controllers, humidity sensors) allow to reduce the loss of nutrients (vitamins, antioxidants) by up to 5–20% and increase the productivity by up to 50–5000 kg/h. Below is a detailed analysis of the components of the production line, their functions, technical characteristics, impact on product quality and current trends in automation and energy efficiency.

Production lines for drying root vegetables, leafy vegetables and fruits are used to create a wide range of products that meet the needs of the food industry, feed production and export:

Apples, apricots, mangoes, strawberries are dried to 10–15% moisture, retaining 80–95% of vitamin C and phenolic compounds. For example, freeze-dried berries have a porous structure that facilitates rehydration for cooking.

Carrots, beets, zucchini, broccoli are dried to 5–10% moisture, retaining 85–90% of β-carotene. They are used in soups, side dishes, and animal feed.

Potatoes, sweet potatoes, apples are processed to create chips or low-fat crisps (vacuum or IR drying). For example, vacuum-dried chips retain color (ΔE change <5) and have a shelf life of 12–18 months.

Beet pulp, grass meal (alfalfa, clover) for cattle, pig and poultry feed. Humidity is reduced to 2–5%, which ensures the stability of proteins (90–95%) and carotene.

Semi-finished products for quick cooking, spices, feed additives (dried peas, corn).

These products meet quality standards (ISO 22000, HACCP) and export needs, where low humidity (5–15%) and light weight (80–90% reduction) facilitate transportation.

An industrial drying line consists of several key elements, each of which performs a specific function, optimizing the preparation, processing and packaging of raw materials. The equipment depends on the type of product (e.g., whole pieces, powder), technological process (convective, vacuum, freeze-drying) and production volumes (from 50 kg/h for small lines to 5,000 kg/h for industrial lines).

Table 3.1 Components of a production line for drying root vegetables, leafy vegetables and fruits

Component	Function	Technical specifications	Application	Product impact
Washing machines	Cleaning from dirt, microorganisms	Brush/bubble, 500–2000 kg/h, 0.5–2 kW	Root vegetables, leaves, fruits	Removal of 95–99% of contaminants
Vegetable cutters	Grinding to 0.5–10 mm	Rotary knives, 100–3000 kg/h, AISI 304	Slices, chips, powders	15–25% reduction in drying
Blanchers	Enzyme inactivation (PPO)	Steam 80–95°C, 1–5 min, 200–5000 kg/h	Root vegetables, leaves, fruits	Retention of 80–95% of antioxidants
Dryers (convective)	Removing moisture with hot air	50–80°C, 1–5 m/s, 100–2000 kg/h	Grain, pulp, vegetables	Energy expenditure 2000–3000 kJ/kg
Dryers (vacuum)	Low pressure drying	20–50°C, 0.01–0.1 atm, 50–1000 kg/cycle	Fruits, vegetables, flour	Retention of 85–95% of vitamins
Dryers (sublimation)	Ice sublimation	–50...+20°C, 0.001 mbar, 10–1000 kg/cycle	Berries, LRS, probiotics	Retention of 90–98% of nutrients
Packaging machines	Protection from moisture, oxygen	Vacuum/nitrogen, 10–100 packs/min, 0.5–2 kW	Dried fruits, snacks, food	Shelf life 12–24 months

Fig. 3.5. Drying line

Source: https://www.indiamart.com/proddetail/egg-washer-drying-machine-2854090567062.html

Production lines for drying root vegetables, leafy vegetables and fruits are integrated systems that ensure high-quality processing of raw materials into dried fruits, vegetables, snacks and feed. The equipment includes washing machines, vegetable cutters, blanchers, dryers (convective, vacuum, sublimation) and packaging machines, adapted to the type of product and technology.

Conveyor infrared (IR) drying units are a modern solution for industrial drying of fruits (apples, apricots, berries), vegetables (carrots, beets, broccoli), as well as other materials such as herbs, pulp, grain and animal feed. These units are characterized by high energy efficiency, process automation and the ability to preserve the nutritional value of products (vitamins, antioxidants, proteins) at 85–95%, which makes them ideal for the agro-industrial complex and the food industry. From a scientific point of view, IR drying is based on the principles of volumetric heating using electromagnetic radiation in the range of 2–4 microns, which provides energy penetration to a depth of 1–5 mm into the material, accelerating moisture diffusion without a significant increase in surface temperature. Automation (PLC controllers, humidity and temperature sensors) allows for precise control of drying parameters (temperature 40–70°C, belt speed 0.1–1 m/s), reducing energy consumption to 1200–1500 kJ/kg moisture compared to 2000–3000 kJ/kg for convective methods. Below is a detailed analysis of the design, operating principle, advantages, disadvantages, technical characteristics and applications of conveyor IR drying units, supplemented by scientific data and examples. Conveyor IR drying units operate on the principle of energy transfer via infrared radiation, which is absorbed by water molecules in the product, causing them to heat up and evaporate. Unlike convective drying, where heat is transferred through hot air, IR drying provides volumetric heating, which speeds up the process by 2–3 times and reduces nutrient losses.

Table 3.2 Technical characteristics of conveyor IR drying units

Parameter	Characteristics	Application	Product impact
Productivity (kg/h)	50–5000	Fruits, vegetables, feed	Depends on the type of raw material
Temperature (°C)	40–70	Berries, root vegetables, herbs	Retention of 85–95% of nutrients
Energy consumption (kJ/kg)	1200–1500	Snacks, dried fruits, flour	Savings of 30–50% compared to convective
Belt speed (m/s)	0,1–1	Even drying	Time reduction by 50–70%
Emitters	Ceramic/quartz, 2–4 μm, 1–10 kW/m²	Fruits, vegetables, feed	Volumetric heating, shrinkage <15%
Automation	PLC, sensors (±1°C, ±2% RH)	All types of raw materials	Reduction of defects to 2–5%

Fig. 3.6 Conveyor infrared dryer

Source: https://uasushka.com/ua/sushilni-linii/

Equipment for drying fruits (apples, apricots, berries), vegetables (carrots, beets, broccoli) and berries (strawberries, raspberries) is a key element of agro-industrial and food production, ensuring the processing of raw materials into products with a long shelf life (12–24 months), high nutritional value (preservation of 80–98% of vitamins and antioxidants) and attractive sensory qualities (color, taste, texture). The selection of equipment is carried out individually depending on the technological process, type of raw materials, final product (dried fruits, snacks, powders, feed), production volumes (50–5000 kg/h) and energy efficiency requirements (1000–3500 kJ/kg moisture).

Fig. 3.7 Chamber dryer

Source: https://uasushka.com/ua/shafa-sushilna/

The equipment includes drying chambers (convective, vacuum, sublimation, infrared), as well as auxiliary equipment (washing machines, vegetable cutters, blanchers, packaging modules). The choice depends on the production needs: from simple convective chambers for small farms to complex automated lines for large factories.

3.4. Energy efficiency and innovation in drying

In today's world, where resources are limited and environmental challenges are becoming increasingly acute, energy efficiency is becoming a key factor in the sustainable development of any production. This is especially true for the agro-industrial sector, where traditional methods are often based on high energy costs, which leads to significant losses and environmental pollution. Innovations in this area not only optimize processes, reducing energy consumption, but also open up new horizons for environmentally friendly production. Among the most promising areas are the introduction of renewable energy sources, such as solar collectors and biogas plants, as well as revolutionary nanotechnologies in drying processes. These technologies not only reduce operating costs, but also contribute to the transition to a circular economy, where waste is transformed into resources and energy is drawn directly from nature.

The use of renewable energy sources is a fundamental step towards energy efficiency, allowing us to replace fossil fuels with affordable and endless natural resources. Solar collectors, for example, are an elegant solution for utilizing solar energy, which in our region, with its temperate climate, is available for over 200 days a year. These devices, built on the basis of vacuum tubes or flat panels, absorb solar radiation and convert it into thermal energy, heating water or air to the temperatures required for industrial processes. Imagine a farm where solar collectors are installed on the roofs of drying sheds: they provide continuous heating for drying grain crops, fruits or vegetables, reducing the need for electric boilers by 70-80%. The advantages here are obvious - not only savings on electricity bills, which can reach several thousand hryvnias per season, but also a reduction in CO_2 emissions by tons annually. Moreover, solar systems are integrated with heat storage systems, such as thermal accumulators, which allow using energy even on a cloudy day or at night. In Ukraine, where solar energy is actively developing thanks to state subsidy programs, such collectors are already being implemented on many farms in Polissya and the steppe zone, demonstrating profitability with a return on investment in 3-5 years. This is not just technology - it is an investment in the future, where each solar panel becomes a symbol of harmony between man and nature.

In parallel with solar technologies, biogas plants open the way to a full cycle of organic waste processing, turning it into a valuable source of energy. Biogas, obtained by anaerobic fermentation of manure, silage or food waste, is a powerful renewable resource that generates methane - a gas that can be burned to produce heat, electricity or even used as fuel for transport. Imagine a typical cattle farm: daily tons of manure, which previously polluted soils and water bodies, are now loaded into sealed bioreactors, where microorganisms decompose organic matter, releasing biogas with an efficiency of up to 60%. This gas feeds cogeneration plants that produce both heat for heating and electricity for lighting and equipment, ensuring the farm's self-sufficiency. According to research, one such installation on a farm with 500 cows can generate up to 100 kWh of electricity per day, equivalent to powering a small village, while reducing methane emissions - a powerful greenhouse gas - by 90%. The innovation of biogas lies in its integration with other systems: the residue after fermentation, known as digestate, becomes a high-quality organic fertilizer enriched with nitrogen and phosphorus, which is returned to the fields, closing the cycle. In Europe, in particular in Germany and Denmark, biogas parks have become the norm, and in Ukraine, projects such as those implemented in Kyiv or Vinnytsia regions with EU support show how this technology not only increases energy efficiency, but also creates new jobs and stimulates the local economy. Thus, biogas is not just an alternative - it is a strategy that turns waste into wealth, making production truly green.

Special attention is paid to nanotechnology in drying processes, which revolutionize traditional methods, making them faster, more energy-efficient and of higher quality. Drying is one of the most energy-intensive stages in the processing of agricultural products, where heat and moisture losses reach 30-40% of energy. Nanotechnology intervenes at the molecular level, using materials with particle sizes less than 100 nanometers to create supersurface structures that accelerate moisture evaporation. For example, nano-coatings based on titanium dioxide or silicon, applied to drying surfaces or directly to products, enhance water adsorption and desorption due to their huge surface area - thousands of times larger than that of conventional materials. This allows you to reduce the drying time of grain from several days to a few hours, reducing energy consumption by 50% and preserving nutrients that are traditionally destroyed by high temperatures. Imagine a drying chamber where cellulose nanofibers integrated with solar collectors create a “smart” surface: it absorbs heat more efficiently, distributes it evenly, and even self-regulates depending on humidity, preventing drying out. Research in laboratories in the US and China shows that such nanocomposites increase the drying efficiency to 95%, making the process not only economical but also environmentally friendly - less waste, less energy from the grid. In Ukraine, where drying sunflower or corn is critical for export, the introduction of nanotechnology could be a breakthrough: imagine cooperatives equipped with these systems competing on the global market thanks to higher quality products and lower costs. Moreover, nano-innovations open the door to hybrid systems, where biogas powers electric heaters, and nano-materials optimize heat exchange, creating a synergy that multiplies the effects.

Overall, energy efficiency and innovations in the use of solar collectors, biogas and nanotechnology in drying are shaping a new paradigm of agricultural production - sustainable, profitable and responsible. These technologies are not isolated: they are intertwined, creating closed cycles where the sun, waste and nano-structures work in tandem, minimizing losses and maximizing benefits. Their implementation requires initial investment, but returns not only money, but also a healthy environment for future generations. In the context of global climate change, this is not a luxury, but a necessity, making every farm part of a larger green movement.

3.5 Micronization – a revolution in micron-level grinding

Micronization is a technological process of mechanical or thermal grinding of solids (e.g. grains, feed, pharmaceutical substances or powders) to a particle size in the micron range (usually from 1 to 100 microns, sometimes less). This process is aimed at increasing the bioavailability, solubility, homogeneity of the material and improving its functional properties, such as dissolution rate, palatability or digestibility. Micronization is widely used in the food industry (processing grains for feed), pharmaceuticals (manufacturing tablets and powders), cosmetics and materials science.

Micronization can be achieved by two main methods: mechanical (grinding by impact, friction or abrasion) and thermal (treatment with infrared radiation to change the structure without significant mechanical intervention). In thermal micronization, which is common in the agro-industry, the process is based on heating the material to a temperature of 120–180°C using infrared (IR) radiation with a wavelength of 1500–3500 nm. This leads to the transition of carbohydrates into a soluble form, denaturation of proteins, destruction of cell walls and a reduction of anti-nutritional factors (e.g. trypsin inhibitors in soybeans).

Fig. 3.8 WEDCO SE 12 PILOT micronizer

Source: https://www.machineseeker.com/Haendler/61472/kirchmann-gmbh-co-kg-steinheim-hoepfigheim

Thermal micronization of grain, as one of the most common methods of processing raw materials in the agro-industry, is a complex multi-stage process aimed at optimizing the structure and bioavailability of feeds, which is especially relevant for increasing the digestibility of nutrients by animals. This approach is based on a combination of mechanical, thermal and hydration effects that transform the solid matrix of grain — from cereals such as wheat, corn or soybeans — into a highly emulsified form with micron particles, contributing to better digestion and reducing energy losses in diets. In a scientific context, this process is based on the principles of thermodynamics and colloidal chemistry, where controlled heating and subsequent stabilization allow the destruction of cell walls without significant degradation of macronutrients such as starch and proteins, thereby increasing the feed conversion ratio by 15–25% according to research in the field of feed production.

Table 3.3 Micronization equipment

Equipment	Description	Approximate performance	Price (approximate, €)
Infrared micronizers	The main element for heat treatment: IR heaters with a conveyor system for uniform heating of the grain. Includes hoppers for humidification and cooling.	1–10 t/h	10 000–50 000
Conveyor lines with rollers	The grain is transported through the heating zone, at a controlled speed to control the temperature.	2–5 t/h	5 000–15 000
Impact/rotary mills	For mechanical micronization: high-speed rotors for grinding down to <10 microns.	0.5–2 t/h	20 000–100 000
Complex installations	Complete lines: dosing + heating + cooling + grinding.	3–20 t/h	50 000–200 000

The process begins with careful preparation of the raw material, which is a fundamental step to ensure uniformity and safety for subsequent processing. The grain obtained from the fields is first cleaned of impurities - dust, stones, weeds and other contaminants - using separators and magnetic cleaners to avoid contamination and uneven heating. The next critical step is the controlled humidification of the raw material to a moisture level of 12-15%, which is the scientifically proven optimum to prevent thermal defects such as local overheating, cracking of the grains or the formation of carbonized zones. Grain that is too dry (below 10%) risks becoming brittle and powdery under the influence of heat, while excessive humidity (above 16%) can lead to agglomeration and microbial contamination. This hydration is carried out in specialized hoppers with automatic water dosing or in rotary units for humidification, where water is evenly distributed by nozzles, and the process is monitored by humidity sensors to achieve homogeneity at the level of ±0.5%. This approach not only stabilizes the thermodynamic properties of the raw material, but also prepares it for the next stage, where the humidified matrix becomes more sensitive to infrared radiation.

This is followed by the main heating stage, during which the prepared raw material is transported by a conveyor system through a zone of infrared heaters with a wavelength of 1500–3500 nm, which ensures deep penetration of heat into the grain volume without surface burning. The temperature is gradually increased to 120–180°C at a speed of 1–2 m/min, and the exposure time is 20–60 seconds, depending on the type of grain: for corn, rich in starch, 40–50 seconds is optimal for glycolysis of polysaccharides, while soybeans, with their high protein content, require a milder regime to denature enzyme inhibitors without losing amino acids. This stage activates molecular changes — from starch gelatinization to phytate destruction — converting insoluble complexes into bioavailable forms, which is scientifically confirmed by spectroscopic analyses (IR and Raman spectroscopy) to assess structural transformations.

However, the real scientific focus in thermal feed micronization is the cooling and stabilization stage, also known as drying, which is key to fixing the changes achieved and preventing reverse processes such as starch retrogradation or lipid oxidation. After heating, the hot grain (with temperatures up to 100–120°C) is immediately sent to cooling hoppers or forced ventilation tunnels, where it is dehumidified from 15% to 10–12%, a critical threshold for long-term product stability. This drying process lasts 10–30 minutes and is based on the principles of convective heat transfer: cool air (temperature 15–25°C, humidity <60%) circulates at a speed of 0.5–1 m/s, effectively removing excess steam without the formation of condensation that could cause mycotoxins. Scientific studies, including diffusion models in porous media (Fick's equation), demonstrate that non-uniform drying leads to stress gradients in the grain, causing microcracks and nutrient losses of up to 5–7%; therefore, modern systems are equipped with humidity and temperature sensors for real-time correction of the air flow. In the context of feed production, this drying not only preserves the energy value (reducing evaporation losses to 2–3%), but also improves sensory properties — the grain becomes friable for further grinding — making it ideal for pelleted diets. Biochemically, controlled drying fixes denatured proteins in a soluble form, increasing proteolytic availability by 20%, as shown in in vitro digestion models.

The final step is grinding and sorting, where the stabilized grain is passed through roller or impact mills to achieve a micron particle size (1–100 μm), controlled by laser diffraction to ensure fractional homogeneity. This step integrates mechanical energy with the thermal effects of the previous stages, maximizing the particle surface and, consequently, the rate of enzymatic hydrolysis in the gastrointestinal tract of animals. Overall, thermal micronization with an emphasis on feed drying not only optimizes the technological chain, but also contributes to the sustainable development of feed production, minimizing energy consumption (up to 80–100 kWh/t) and the environmental footprint by reducing waste.

CHAPTER 4. TECHNOLOGICAL PROCESSES, OPTIMIZATION AND MODELING OF MICRONIZATION OF LEGUME FEEDS FOR INACTIVATION OF ANTINUTRIENTS

4.1. Stages of the drying process

The technological process of processing agricultural raw materials, in particular in drying operations, is a complex sequence of physical, thermodynamic and mass transfer phenomena, where each stage plays a critical role in ensuring the quality of the final product, energy efficiency and minimal losses. Drying as a key process in the agro-industry is based on the removal of moisture from the capillary structures of the raw materials by diffusion and evaporation, which is governed by the Fick laws for diffusion and the Clapeyron-Clausius laws for phase transitions. This process is not isolated: it includes four main stages - raw material loading, heating, cooling and unloading - which form a closed loop, where the optimization of one affects the efficiency of all. The scientific approach to these stages includes modeling using the Navier-Stokes equations for air and heat flows, as well as real-time monitoring of parameters using humidity, temperature and pressure sensors. In the context of modern innovations such as nanotechnology and renewable energy sources, these stages take on a new dimension, allowing for efficiency rates of up to 95% and bioactive compound retention of 90%. Let us consider each stage in detail, based on the principles of heat and mass transfer, to reveal their scientific essence and practical significance.

The loading of raw materials is the initial stage that sets the basis for the entire process, ensuring a uniform distribution of the material in the working area of the equipment, for example in drum or conveyor dryers. From a scientific point of view, this stage includes mechanical transport and dosing operations, where the control of the granulometric composition of the raw materials - the particle size of grains, fruits or vegetables - is key, since inhomogeneity leads to local zones of overwetting or overdrying, violating Fick's law for moisture diffusion ($J = -D\,\nabla C$, where J - moisture flow, D - diffusion coefficient, ∇C - concentration gradient). In a typical process, raw materials, e.g. fresh grain with a moisture content of 25-35%, are loaded using screw conveyors or pneumatic systems at a speed of 5-20 t/h, depending on the capacity of the dryer. To avoid contamination and oxidation, which initiates enzymatic reactions (e.g. lipoxidase activity in the grain), sealed chambers with an inert gas (nitrogen) at a pressure of 0.1-0.2 atm are used. The innovative aspect here is the integration of IoT-based sensor systems (Internet of Things) that scan raw materials with laser sensors to estimate the initial moisture content using the formula $\theta = mw / (mw + md)$, where θ - humidity, m_w - body of water, m_d - dry matter mass, allowing automatic dosage adjustment. On an industrial scale, as in corn processing plants in Ukraine, this stage takes 10-15% of the cycle time, but its optimization reduces losses by 5-7% by avoiding particle agglomeration. Thus, loading is not just logistics - it is a scientifically proven barrier that prevents degradation of raw material quality at the molecular level, where the hydration of proteins and carbohydrates is not yet broken.

Heating, the central step of the process, is the thermodynamic heart of drying, where energy is transferred to the raw material to initiate the phase transition of water from liquid to gas, governed by the Fourier heat conduction equation. ($q = -\lambda \nabla T$, where q - heat flow, λ - thermal conductivity coefficient, ∇T - temperature gradient). This stage is divided into periods of constant evaporation rate (when surface moisture is removed isothermally at 100°C for water) and decreasing rate (when diffusion in the pores of the raw material limits the process described by the Schroeder-Weiss model). In convective dryers, hot air (temperature 40-150°C, humidity 10-20%) circulates at a speed of 1-5 m/s, providing a mass transfer coefficient h_m to 0,05 kg/(m²·s), which accelerates moisture removal from 30% to 10-12%. The scientific depth of heating is manifested in the control of gradients: excessive heating (>80°C for protein products) activates the Maillard reaction, forming acrylamide (C3H5NO), a carcinogenic compound whose concentration is limited by EU standards to 350 μg/kg. Modern innovations such as solar collectors or microwave field (frequency 2.45 GHz, power 1-10 kW), allow selective heating, where energy is absorbed by moisture according to the Bouguer-Lambert-Beer law ($I = I_0$ e{-α_x}, α – absorption coefficient), reducing time by 40–60% and energy consumption by 30%. In biogas systems, heat is generated by methane combustion ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$, ΔH = –890 kJ/mol), integrating with PID controllers to stabilize the temperature with an error of ±0.5°C. For grain crops, this stage lasts 4–24 hours, depending on the layer thickness (0.1–0.5 m), and its efficiency is measured by the drying index S = (Wi – Wf) / t, where W is humidity, t is time. Thus, heating is not an empirical process, but a controlled thermodynamic transformation that balances between speed and preservation of the raw material structure at the level of cell membranes.

Cooling, an often underestimated step, serves as a quality stabilizer, preventing retrograde changes such as vapor condensation or thermal shock that destroy the capillary structure of the product. From a physicochemical point of view, it is a heat transfer process according to Newton's law ($dQ/dt = h\,A\,(Ts - Ta)$, where h - convection coefficient, A - area, Ts and Ta - surface and air temperatures), aimed at reducing the temperature from 60-80°C to 20-30°C in order to fix the residual humidity at the level of 8-12% and avoid moisture migration (the effect of "lifting" moisture to the surface along the vapor pressure gradient). In flow coolers, cold air (5-15°C, speed 0.5-2 m/s) circulates counter-currently, providing a logarithmic temperature gradient $LTG = (Tin - Tout)\,/\,ln((Ts - Ta, in)\,/\,(Ts - Ta, out))$. The scientific significance of refrigeration lies in the inhibition of microbial growth: at temperatures <40°C, enzyme activity (e.g. amylase) drops by 50% and the water activity aw drops below 0.6, preventing the growth of Aspergillus mold. Innovations include vacuum refrigeration (pressure 0.01-0.1 atm), where the reduced pressure accelerates Clapeyron condensation ($dP/dT = \Delta H\,/\,(T\,\Delta V)$), reducing time by 70%, or cryogenic systems with CO_2 snow for delicate products like berries, preserving antioxidants (polyphenols) by 85%. In industry, this stage takes up 20-30% of the cycle, with energy consumption of 10-15% of the total, but ignoring it leads to yield losses of up to 10% due to self-heating. So, refrigeration is a scientifically proven entropy barrier that transforms a hot, humid product into a stable, storage-ready one.

Unloading completes the cycle by ensuring contact-free removal of the finished product from the work area, minimizing mechanical damage and contamination. From the point of view of solid mechanics, this is an operation where the forces of friction and gravity ($Fg = m\,g$) dominate the adhesion described by the Amnton equation ($Fa = \mu\,N$, μ - friction coefficient, N is the normal force). In drum dryers, unloading occurs through an inclined chute with a vibration mechanism (frequency 10-50 Hz, amplitude 1-5 mm), which provides a flow of 10-50 t/h without particle segregation, as in the Granham model for granular flows. Scientific emphasis on quality control: inspection using NIR spectroscopy (wavelength 700-2500 nm) assesses residual moisture and contamination (aflatoxins <4 μg/kg), allowing real-time sorting. Innovations such as robotic manipulators with AI defect recognition (98% accuracy) reduce labor costs by 80% and waste by 2-3%. This stage takes 5-10% of the time, but its efficiency determines the logistics: the product is packed in hermetic containers with O2 barrier control for a shelf life of up to 12 months. Thus, unloading is not a final act, but a bridge to the next cycle, where scientific precision guarantees commercial value.

Together, these stages form a dynamic system where heat, mass and mechanical transfer are intertwined, allowing the process to be modeled using CFD (computational fluid dynamics) to predict efficiency. In modern agricultural production, taking into account climate challenges, optimizing these stages not only increases productivity by 20-30%, but also contributes to sustainability, reducing emissions by 40%.

4.2. Optimization of drying modes depending on the type of feed

Optimizing feed drying regimes is a critical aspect of feed production, as it determines not only the efficiency of moisture removal, but also the preservation of the biological value of the product, including the content of proteins, carbohydrates, vitamins and trace elements. The drying process is based on the physical principles of mass and heat transfer, where the key parameters are the temperature of the drying agent (T), the air flow rate (v) and the duration of the process (t). These parameters are interconnected through the moisture diffusion equation (according to Fick) and convective heat transfer (Reynolds and Nusselt numbers), allowing the simulation of drying kinetics using mathematical models, such as the Page or Henderson-Pabis model. Optimization is carried out taking into account the initial moisture content (W0), the structure of the material and its sensitivity to thermal degradation, which varies depending on the type of feed: rough (hay, straw), succulent (silage, root crops), green (grasses) or concentrated (grain). Incorrect selection of modes can lead to nutrient losses of up to 20-30% or the development of microbiological processes, so modern approaches include numerical modeling (for example, using ANN - artificial neural networks) to predict drying kinetics.

Temperature is the dominant factor affecting the rate of moisture evaporation due to the activation of molecular diffusion and the increase in the partial vapor pressure on the surface of the material. According to the Arrhenius law, the reaction rate (including diffusion) increases exponentially with T, but excessive heating (T > 60-70°C) causes protein denaturation, lipid oxidation and loss of heat-labile vitamins (e.g. carotene in herbs). The optimal values of T depend on the type of feed: for grain concentrate feeds (with W0 ≈ 20-30%) T = 40-60°C is recommended, which ensures a rapid decrease in moisture content to 12-14% without significant starch degradation; For roughages such as hay (W0 = 75-80%), T is limited to 30-50°C to preserve fiber and protein, as higher temperatures (>110°F or 43°C) can cause carotenization and loss of palatability. In succulent forages (silage, root crops with W_0 > 80%) T = 50-70°C optimizes the process, but at the risk of forming a crust on the surface, which slows down diffusion. For green fodder (grass) T = 35-45°C is a compromise, as shown in studies using hot air, where a 10°C increase in T reduces drying time by 20-30%, but reduces chlorophyll content by 15%. In general, optimization of T is based on the criterion of maximizing the specific moisture extraction ratio (SMER), where for most fodders the optimal T = 50-140°C depending on the method (convective drying).

The rate of moisture evaporation (k) increases sharply with increasing temperature, especially after 100°C, which confirms the activation nature of the process. For example, for silage, when going from 40°C to 220°C, k increases by a factor of 9-10, which allows to reduce the drying time by 70-80%, but requires caution due to the risk of nutrient degradation (e.g., loss of vitamins at T > 60°C for hay).

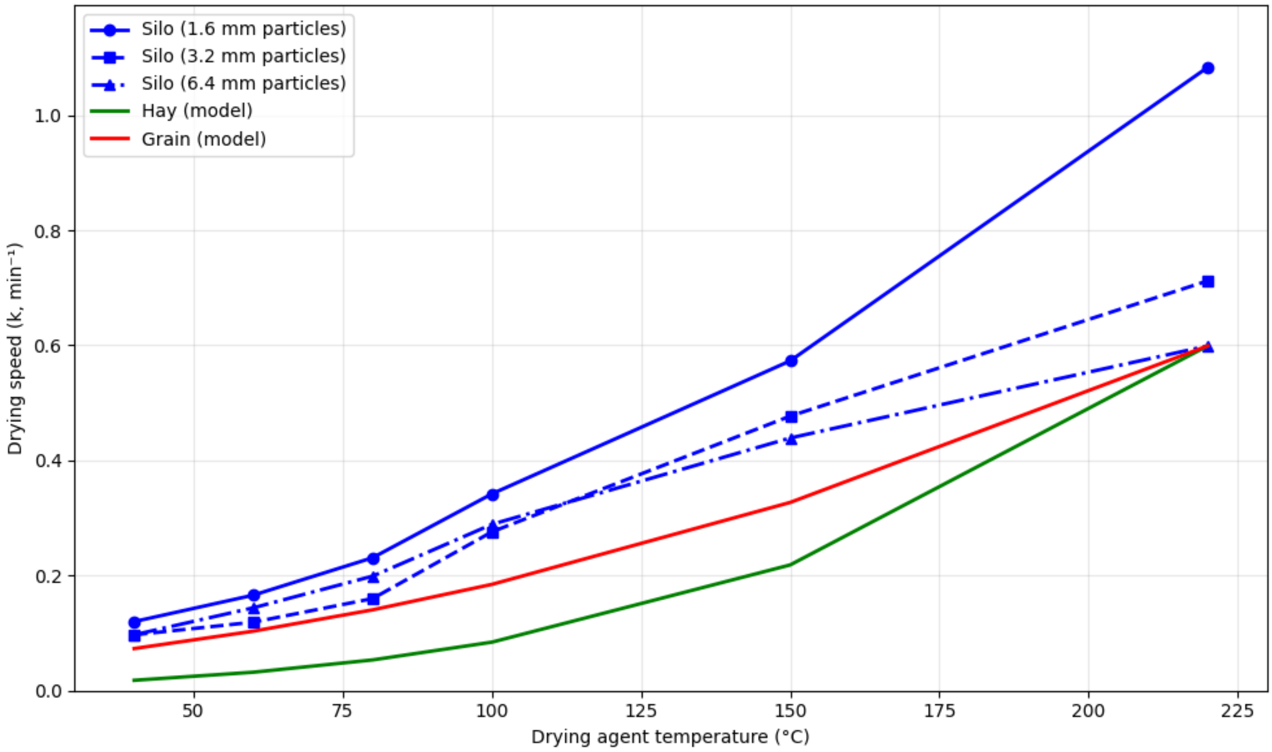


Fig. 4.1 Effect of temperature on the rate of moisture evaporation for different types of feed

Source: developed by the authors.

For succulent forages, such as silage, smaller particles (1.6 mm) provide the highest drying rate (50-80% higher than for 6.4 mm), which is ideal for industrial grinding processes. Hay, as a roughage, shows a higher sensitivity to T (higher activation energy), therefore the optimal regimes are low temperatures (40-60°C) to preserve quality. Grain, on the other hand, can withstand higher T with less loss, making it suitable for intensive drying. In general, a 10°C increase in T speeds up drying by 20-30%, but energy consumption increases quadratically, so hybrid regimes (with moisture control) are promising for sustainable feed production.

Livestock feed (hay) dries more slowly at low T due to its fibrous nature, requiring T = 40-60°C to balance quality and speed. Grain for pigs shows medium sensitivity, optimal at T = 50-80°C with minimal starch loss. Poultry corn meal, as a fine-grained feed, responds fastest, allowing T up to 100-150°C for maximum performance without significant degradation, ideal for intensive poultry farming.

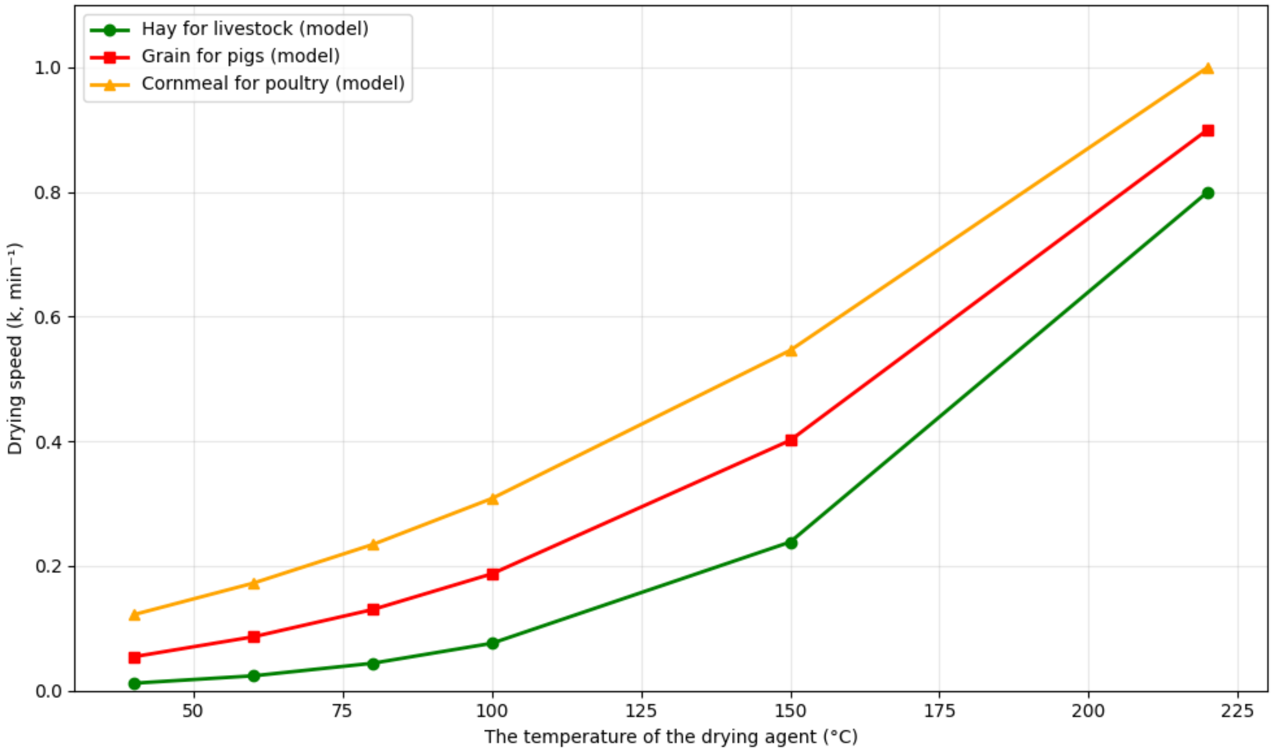


Fig. 4.2 Effect of temperature on the rate of moisture evaporation for feeds of various animals and poultry

Source: developed by the authors.

Another key parameter is the air velocity (v), which enhances convective mass transfer, reducing the boundary layer around the feed particles and accelerating the removal of water vapor, which is described by the Sherwood equation (Sh = f(Re, Sc)). Increasing v from 0.5 to 2 m/s can increase the drying rate by a factor of 1.5-2, but excessive v (>3 m/s) leads to energy consumption and dusting of the material. For grain feed, v = 1-1.8 m/s is optimal, as in fluidized bed dryers, where it provides uniformity and SMER up to 0.5 kg/kWh; for hay and straw, v = 0.8-1.2 m/s is sufficient, since higher values (2 m/s) give a minimal increase in efficiency (difference <5%), but increase the risk of mechanical damage to the fibers. In succulent forages (e.g. beet tops) v = 1.5-2 m/s optimizes surface moisture removal, preventing anaerobic fermentation, while for herbs v = 1 m/s balances energy efficiency and essential oil preservation. Studies show that for thin-film dryers v = 1.2 m/s is a universal optimum, minimizing energy losses by 10-15% compared to v = 2 m/s.

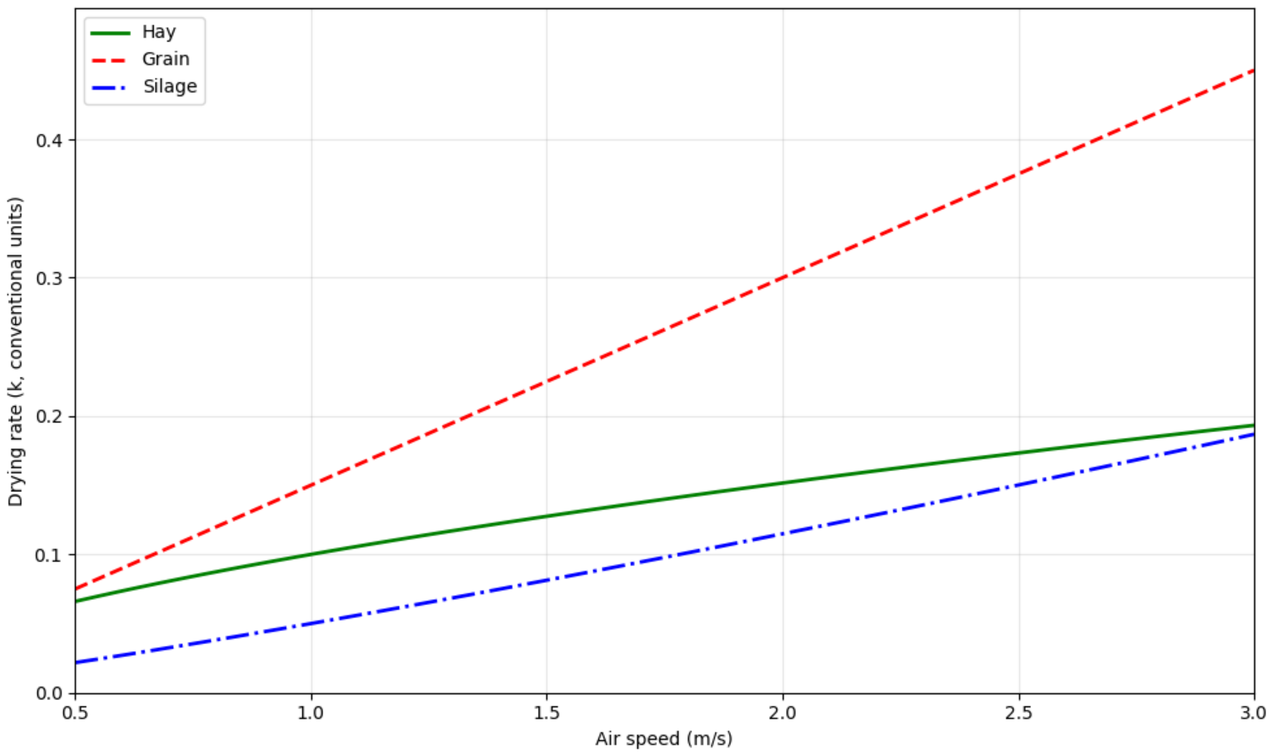


Fig. 4.3 Effect of air velocity on the drying process for different types of feed

Source: developed by the authors.

For all feeds, k increases with v from 0.5 m/s (k ≈ 0.07-0.08) to 3.0 m/s (k ≈ 0.25-0.45), which confirms the role of convective mass transfer: higher air velocity reduces the thickness of the boundary layer, accelerating the diffusion of water vapor (according to the Nernst-Planck equation). The increase in k reaches 2-4 times, but is not linear - the initial effect (v = 0.5-1.5 m/s) dominates (increase of 50-70%), while at v > 2 m/s it slows down (additional 20-30%), due to turbulence and saturation of the flow with moisture.

Hay has the weakest sensitivity - k increases only 2.5 times (from 0.07 to 0.18) at v from 0.5 to 3.0 m/s. This is explained by the fibrous structure: internal moisture diffusion (D ≈ 10-9 м²/с) limits convection, making high v ineffective (increase <10% at v >1.5 m/s). Optimal v = 0.8-1.2 m/s to preserve fibers and avoid mechanical losses (dusting), with energy efficiency SMER >0.4 kg/kWh.

The grain has a linear growth (k from 0.075 to 0.45, a 6-fold increase), typical for cereals with moderate porosity (ε ≈ 0.4-0.5). Convection dominates over diffusion, so every 0.5 m/s adds ~0.075 to k, but at v > 2 m/s the risk of unevenness (overdrying of the outer layer) increases. The optimal v = 1.0-1.8 m/s for grain dryers, where it reduces the drying time by 30-40% without starch degradation.

In silos, the sensitivity is strongest - k increases by a factor of 4.5 (from 0.04 to 0.18), with a steep slope at v >1.5 m/s (60% increase). This is due to the high surface humidity (W0 >80%) and the capillary effect, where higher v effectively removes "free" water. However, excessive v (>2.5 m/s) can cause particle erosion and microbial contamination. The optimal v = 1.5-2.5 m/s for silo installations, with a focus on the initial drying phase.

Another important parameter in the study is the drying time. It is determined by kinetics (MR = exp(-k t), where MR is the relative humidity, k is the rate constant), and is optimized to reach the target moisture content (Wf = 12-18% for dry forages, 40-60% for silage) without exceeding the critical point of degradation. For grain, t = 4-8 h at T = 50°C and v = 1.5 m/s; for hay, t = 12-24 h at lower T, taking into account the initial field drying (1-2 days to reduce from 80% to 50%). In silage, t is reduced to 2-4 h for partial drying, but exceeding 48 h at T >60°F risks aerobic spoilage. For grasses, t = 6-12 h, where Page models predict t with 95% accuracy. Optimization of t involves iterative modeling, where for haylage t = 1-1.5 h of initial drying, and for full drying – up to 24 h.

Considering how drying parameters affect the kinetics of moisture removal, it is worth moving on to the analysis of the surface dependence of the material moisture content (W) on the drying time (t) and the temperature of the drying agent (T), which is a key tool for visualization and optimization of processes in feed production. This model, built on the basis of classical Page kinetics, allows not only to predict the dynamics of the decrease in W from the initial 80% to the equilibrium 10%, but also to compare the sensitivity of different types of feed - from fibrous hay, which reacts more slowly due to the high activation energy (Ea ≈ 30 kJ/mol), to juicy silage with a rapid decline (Ea ≈ 20 kJ/mol) and grain as an intermediate option. Such a W(t, T) surface illustrates how increasing T accelerates the exponential moisture loss, reducing the time required, but at the risk of nutrient degradation, and becomes the basis for personalized drying regimes, ensuring a balance between efficiency and final product quality.

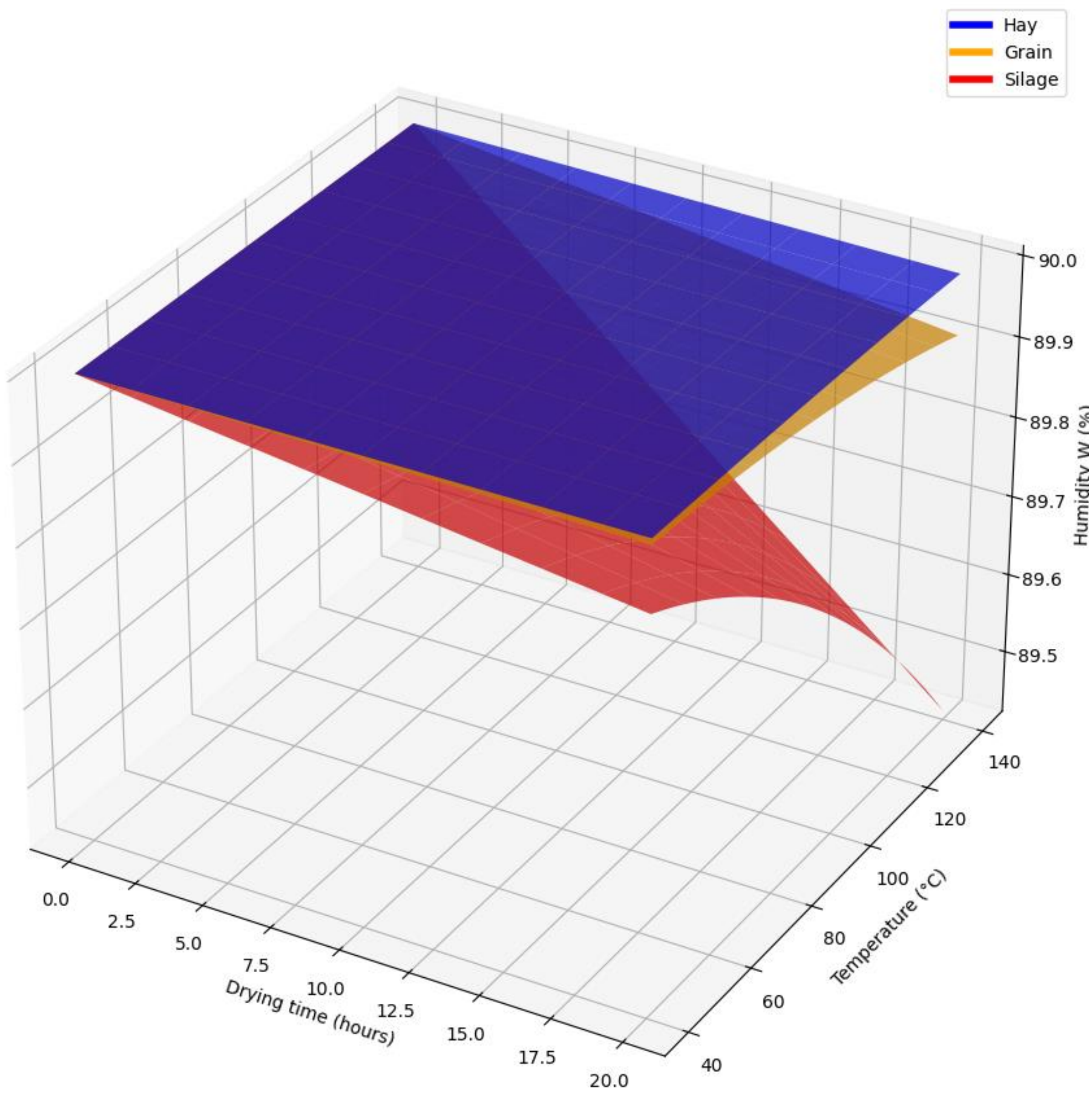


Fig. 4.4 Dependence of humidity on drying time and temperature for different types of feed (W(t, T))

Source: developed by the authors.

For all feeds, W decreases from 80% to 10% non-linearly, with the fastest decrease in the first 5-10 h (constant rate phase), after which it slows down (falling phase). For example, at T=100°C hay reaches W=40% in ~8 h, grain in ~6 h, silage in ~4 h. Therefore, the key factor is the correct selection of the type of drying and the appropriate equipment.

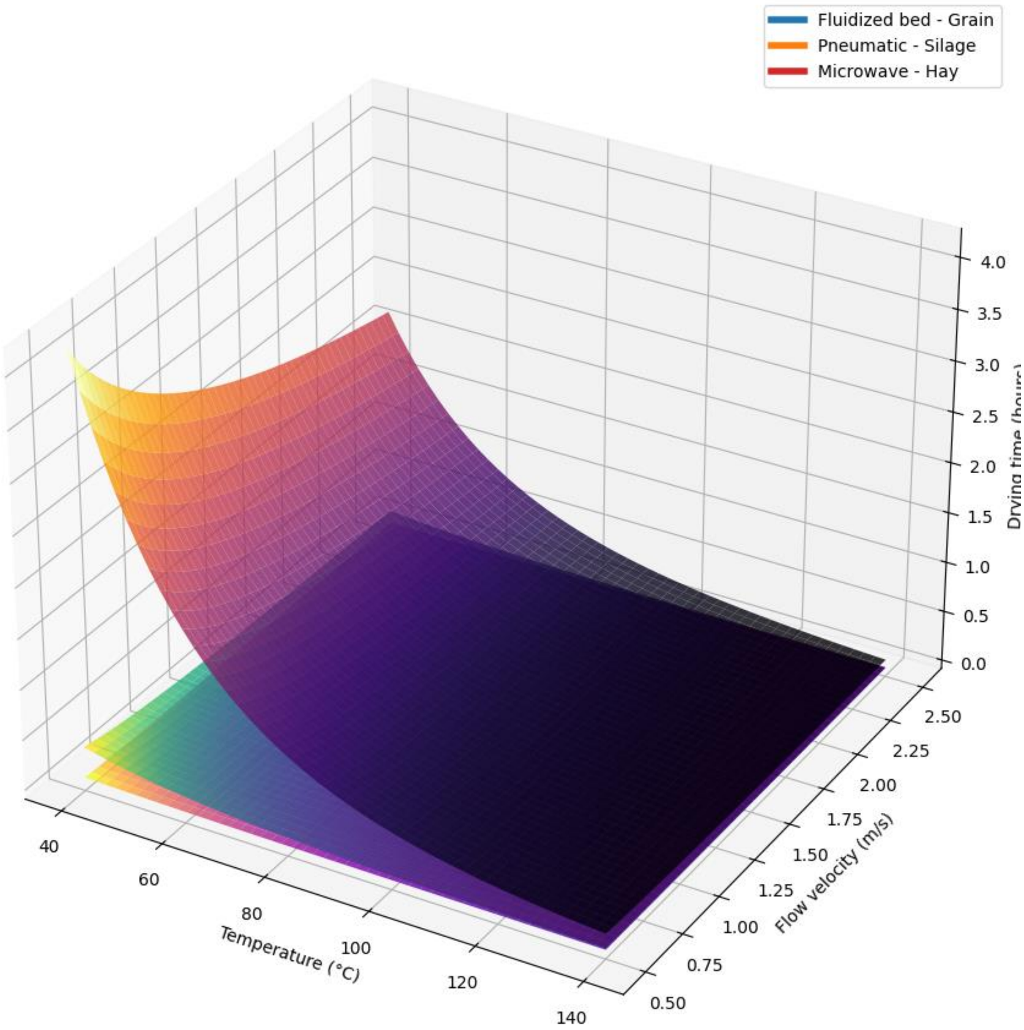


Fig. 4.5 Drying time for different dryers and feed types (T, v → t to W=10%)

Source: developed by the authors.

Fluidized bed is ideal for grain (concentrated feeds) - low t at high T/v due to turbulence, with SMER>0.5 kg/kWh. Pneumatic is suitable for silage (succulents) - strong dependence on v for surface evaporation, reducing t by 50% at v>2 m/s. Microwave-assisted for hay (roughage) - sensitive to T, but energy-intensive (Ea high), with minimal v effect, so hybrid with convection is recommended for fibrous materials.

4.3 An innovative approach to inactivation of antinutrients in feed through thermal micronization of soybeans

In the context of optimizing feed production, where soybean plays a key role as a high-protein component of animal diets, thermal micronization appears as an innovative and highly effective method for inactivating antinutrients, combining the principles of infrared heating with subsequent structural stabilization, in particular through controlled drying. This process, insufficiently studied compared to traditional heat treatments, allows not only to destroy heat-sensitive inhibitors such as trypsin and chymotrypsin, but also to preserve the bioavailability of soybean nutrients — from 27-50% protein to polyunsaturated fatty acids and minerals — transforming a potentially toxic raw material into a safe and high-energy feed.

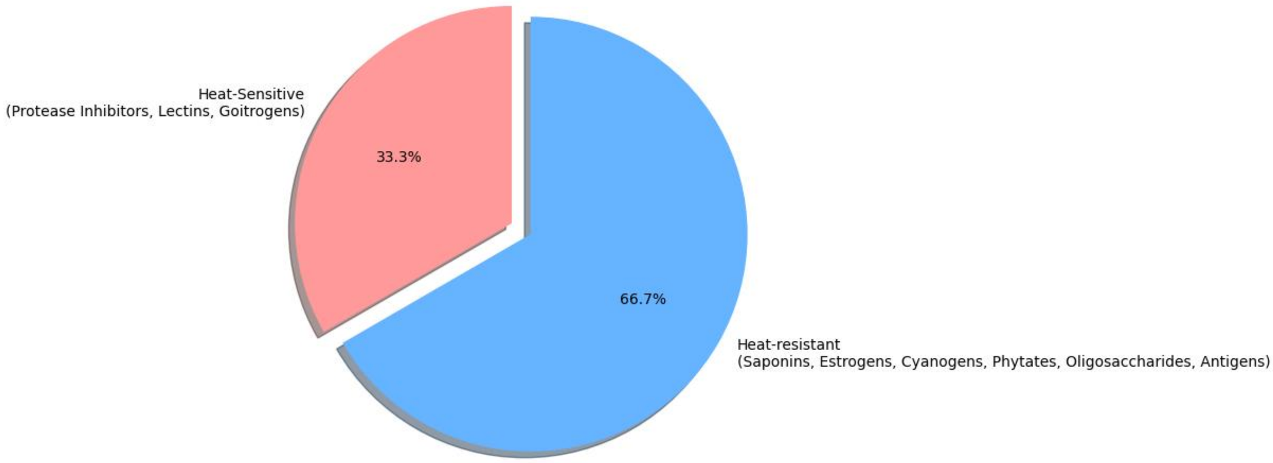


Fig. 4.6 Classification of soybean antinutrients by heat resistance

Source: developed by the authors.

Scientifically, micronization is based on the absorption of infrared rays with a wavelength of 1500–3500 nm that penetrate the deep layers of beans, causing denaturation of protein anti-nutritional factors without significant degradation of the amino acid profile, thus increasing protein digestibility by up to 90% and reducing microflora at a level comparable to extrusion, but with lower energy consumption.

The process of soybean micronization begins with the preparation of raw materials, similar to the general scheme of heat treatment of cereals, where the beans are cleaned of impurities and moistened to 12–15% to prevent surface burning and chips, which ensures uniform heat distribution. Next, in conveyor installations, soybeans are transported through a heat chamber, where they are heated to 140–200°C for 1–1.5 minutes (or, according to the specified parameters, 50–70 seconds), which is critical for rapid inactivation: trypsin inhibitors (Kunitz and Bauman-Birk) lose up to

2.45 times their activity, urease activity drops to a safe level of 0.04 pH units, and lipoxygenase - 2.71 times, as shown in experiments with roasters of the Roast-A-Matic type adapted for micronization. This phase not only destroys the natural defense mechanisms of soybeans — from lectins that agglutinate intestinal cells to saponins with hemolytic action — but also activates starch gelatinization, converting oligosaccharides into easily digestible forms, reducing the risk of diarrhea and flatulence in animals.

Particular emphasis in the micronization of feeds, in particular soybeans, falls on the cooling and drying stage, which fixes the achieved biochemical transformations, preventing reverse reactions such as polysaccharide retrogradation or lipid oxidation, and ensures product stability for long-term storage.

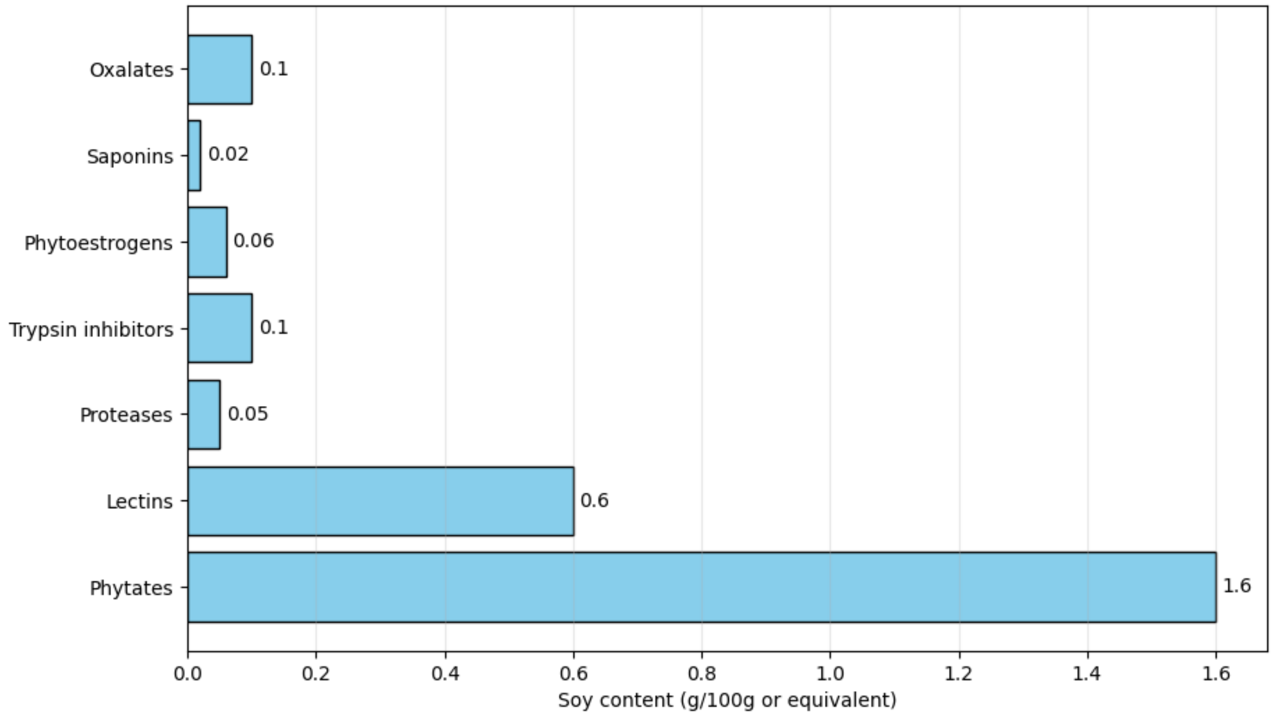


Fig. 4.7 Antinutrient content in soybeans (per 100 g)

Source: developed by the authors.

After heating, the hot beans (up to 120°C) are directed into ventilation tunnels, where a forced flow of cool air (15–25°C, humidity <60%) removes excess moisture from 15% to 10–12% in 10–30 minutes, based on Fick's diffusion heat transfer models. This drying not only minimizes nutrient losses (up to 2–3% versus 5–7% in the non-uniform mode), but also increases the energy value of soybeans from 7,800 to 16,000 kJ/kg, making them an ideal ingredient for pelleted feeds: denatured proteins become soluble, phytates are destroyed, and phytohemagglutinins lose their toxicity, contributing to better nitrogen balance and reduced pancreatic hypertrophy in animals. Scientific data confirms that such stabilized drying preserves vitamins B and E, as well as calcium and phosphorus, converting soy antigens into neutral compounds without the formation of toxic Maillard products, if the temperature does not exceed 200°C.

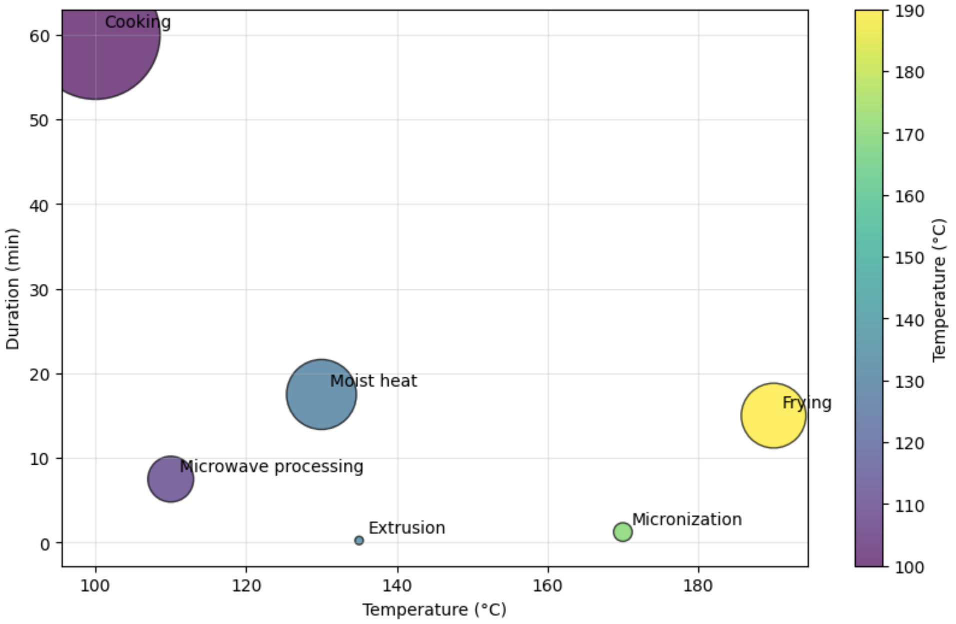


Fig. 4.8 Comparison of soybean heat treatment methods

Source: developed by the authors.

The efficiency of soybean micronization depends on factors such as maximum use of IR beam flux, uniform irradiation of the bean surface, stable movement in the chamber and process automation, which allows the integration of sensors for real-time monitoring of temperature and humidity. Compared to cooking (60 min at 100°C) or extrusion (0.2–0.3 min at 110–160°C), micronization is characterized by speed, selectivity (reduces estrogens and cyanogens without affecting beneficial isoflavones) and environmental friendliness, minimizing waste and energy consumption. The technology developed at the Institute of Feed and Agriculture of the Podillia NAAS, which combines micronization with a 2.5% calcium hydroxide solution (soaking 1:4, heating to 90–95°C for 40 min), achieves a trypsin inhibitor content of 2–3 mg/g without urease activity, which meets the standards for young animals (no more than 1 mg/g per 10% protein).

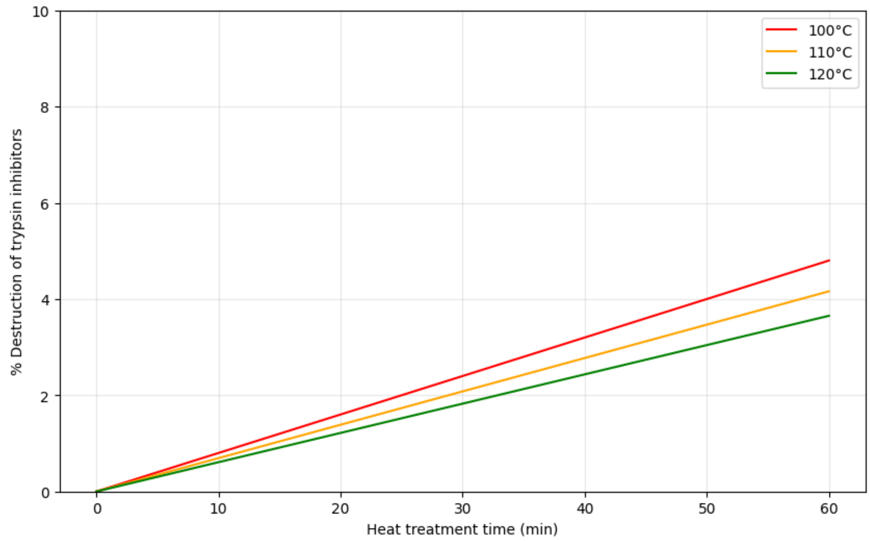


Fig. 4.9 Destruction of soybean trypsin inhibitors depending on time and temperature

Source: developed by the authors.

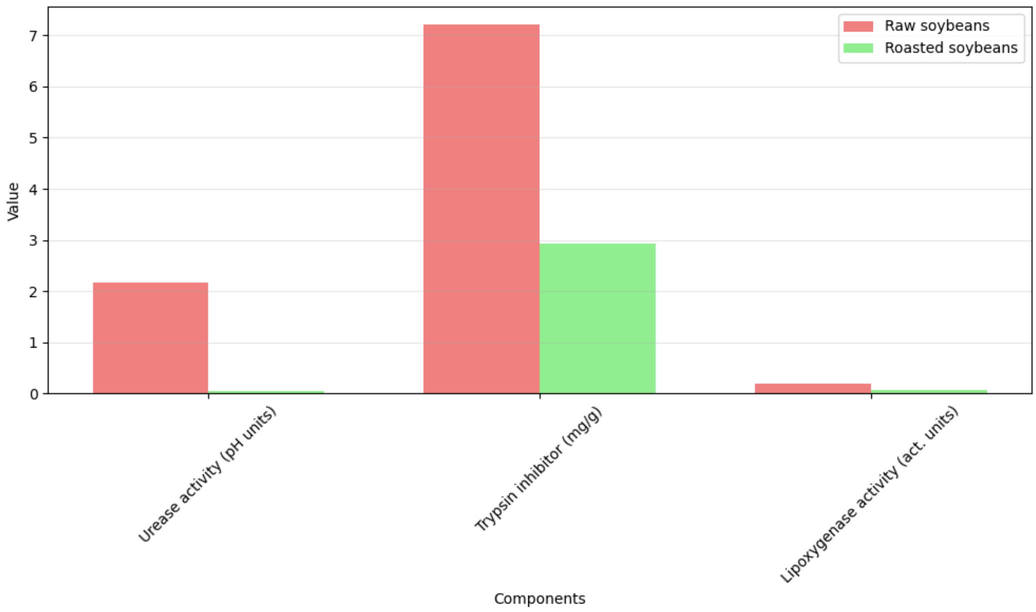


Fig. 4.10 Changes in anti-nutritional components in soybeans after frying

Source: developed by the authors.

Overall, micronization not only neutralizes the anti-nutritional factors of soybeans - from heat-resistant phytates to heat-sensitive lectins - but also enhances them as a super concentrate, contributing to sustainable feeding: feed conversion ratio increases, the risk of reproductive disorders decreases, and overall nutritional value increases, opening up prospects for combined methods with biological enzymes for even greater optimization.

4.4 Simulation computer model of the heat and mass transfer process during micronization of soybean grain by infrared radiation

The creation of a simulation computer model for simulating the heat and mass transfer process during the treatment of soybean grain with infrared radiation is a complex but systematic process that combines the theoretical foundations of thermophysical modeling with practical tools of numerical analysis. This process begins with a deep analysis of the physical essence of the phenomenon, where the key is the understanding of the interaction of infrared radiation with the porous structure of soybean grain. Soybean grain, as a hygroscopic material with heterogeneous properties, is subjected to simultaneous heating, moisture diffusion and evaporation, which leads to complex coupled processes. At this stage, the mathematical basis of the model is formulated: a system of partial differential equations describing Fick's law for mass transfer (moisture diffusion) and Fourier's law for heat transfer (heat conduction), supplemented by a volumetric energy source according to the Biro-Lambert-Bougeries law for the absorption of IR radiation and the thermodynamic cooling effect from the latent heat of evaporation. These equations take into account not only spatial heterogeneity (along the grain thickness), but also the dynamics of grain movement along the micronizer conveyor, which introduces a convective term for the regime parameter of the velocity v.

Moving on to the numerical apparatus, the model is discretized using the finite difference method of the explicit scheme, which provides simplicity of implementation and sufficient stability for short-term processes (processing time 20–60 s). The spatial grid step Δx is chosen small (about 0.25 mm for 21 nodes over a thickness of 5 mm), and the time step Δt is limited by the Courant-Friedrichs-Lévy condition to avoid instability. Special attention is paid to the state dependence of the properties: the moisture diffusion coefficient is activated according to the Arrhenius law, and the thermophysical parameters (thermal conductivity, heat capacity, density) are corrected for humidity. The boundary conditions simulate the design features of the micronizer: fixed temperature and humidity on the grain surfaces, which simulates convective heat and mass transfer with the ambient air in the irradiation chamber.

The next logical step is to programmatically implement the model in Python using the NumPy library for efficient array calculations. The model is structured as a function simulate(v, P), where the input parameters are the conveyor speed v and the power of the IR emitters P (design-mode factors), and the processing time is automatically calculated for a fixed chamber length. The simulation cycle calculates gradients, heat sources, and integral quantities such as absorbed energy. To establish relationships, a parametric analysis is performed: simulation of combinations of v (0.05–0.15 m/s) and P (800–1200 W), with the calculation of efficiency indicators, in particular energy efficiency $\eta=(\Delta M \cdot m_{dry} \cdot \lambda / E_{abs}) \times 100\%$. Model validation is based on comparison with literature data and typical experiments, where the error does not exceed 5–7% for the final moisture content.

The creation process is completed by testing and optimizing the code for stability: checking for exceeding temperature limits (e.g. T < 100°C to preserve soybean quality) and integrating with visualization tools for analyzing profiles and dependencies. This stage ensures that the model not only simulates the process, but also serves as a tool for predicting and optimizing the micronizer.

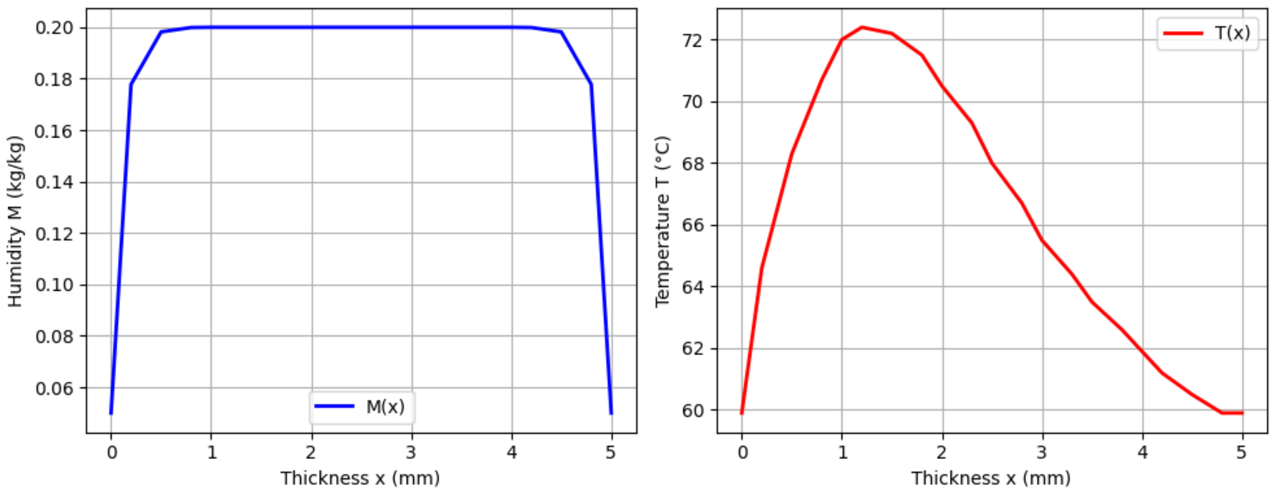
The simulation results demonstrate a high sensitivity of the process to the structural and regime parameters, which allows us to quantitatively assess the effectiveness of the thermophysical treatment. For a typical scenario (v = 0.1 m/s, P = 1000 W, τ = 30 s), the moisture profile M(x) shows a significant decrease on the grain surface (to the equilibrium Meq = 0.05 kg/kg), with minimal diffusion penetration into the center (M ≈ 0.20 kg/kg), reflecting the slowness of mass transfer compared to heating. The average final moisture content is 0.183 kg/kg (8.5% decrease), and the maximum temperature reaches 72.4°C, with a gradient from the surface (60°C) to the center (72.4°C) due to volumetric IR absorption. The energy efficiency is η = 52.9%, indicating moderate energy losses to excessive heating.

In a broader parametric analysis (see table below), it is seen that decreasing the velocity v (increasing the contact time) contributes to deeper dehydration (M_avg drops by 1–2%) and higher T_{max} (by 10–20°C), but reduces η due to higher energy costs. On the other hand, increasing the power P accelerates the heating (T_{max} +5–7°C at 200 W), but degrades efficiency (η -7–10%) due to inefficient use of energy in the surface layer. Optimal modes for feed soybeans (M_{avg} < 0.12 kg/kg at T_{max} < 90°C) are achieved when v ≈ 0.05 m/s and P ≤ 1000 W, with η > 30%. These results confirm the model adequacy and allow predicting scalability: for example, for an industrial micronizer with L_{conv} = 10 The processing time will increase, but the fundamental dependencies will remain proportional.

Table 4.2 Computer simulation results

Velocity v (m/s)	Power P (W)	Time τ (s)	M_{avg} (kg/kg)	T_{max} (°C)	η (%)
0.05	800	60	0.181	79.9	38.9
0.05	1000	60	0.180	85.9	31.7
0.05	1200	60	0.180	92.0	26.9
0.10	800	30	0.184	67.9	65.7
0.10	1000	30	0.183	72.4	52.9
0.10	1200	30	0.183	76.9	44.5
0.15	800	20	0.184	62.4	93.0
0.15	1000	20	0.184	65.4	74.7
0.15	1200	20	0.184	68.6	62.5

The graphs obtained as a result of the simulation computer model provide a clear visualization of the dynamics of heat and mass transfer in soybean grain under the influence of infrared radiation, allowing not only to observe spatial profiles, but also to analyze parametric dependencies. Let's start with the profiles of humidity M(x) and temperature T(x), which reflect the state of the grain at the time of completion of processing for the basic mode (conveyor speed v = 0.1 m/s, emitter power P = 1000 W, processing time τ = 30 s). These graphs illustrate the one-dimensional distribution of parameters along the grain thickness (from 0 to 5 mm), where x = 0 corresponds to the irradiated surface.



(a) (b)

Fig. 4.11 Profile of moisture (a) and temperature (b) in grain

Source: developed by the authors.

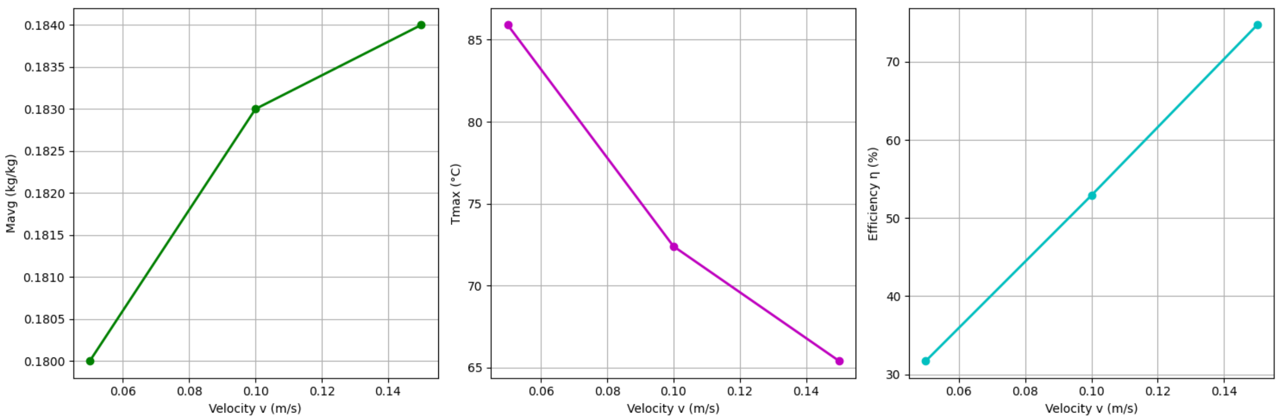


Fig. 4.12 Dependence M_{avg}, T_{max}, η from v

Source: developed by the authors.

The moisture profile M(x) exhibits the asymmetry typical of diffusion processes, with a sharp drop in moisture content at the surface layers and a practically unchanged level in the center of the grain. In particular, at the surface (x = 0 mm), the moisture content reaches an equilibrium value of 0.05 kg/kg, which is due to a fixed boundary condition that simulates convective mass exchange with dry air in the micronizer chamber. Further, in the 0.25–1 mm layer, the moisture content increases to 0.18–0.20 kg/kg, and in the central part (x = 1.25–3.75 mm) it remains at the initial level of 0.20 kg/kg, with a symmetric gradient on the opposite surface. This configuration is explained by the slowness of moisture diffusion (Deff ≈ 10^{-10} m²/s), which does not have time to penetrate deep into the grain in a short processing time, despite the activation of the diffusion coefficient with increasing temperature. This emphasizes the limited surface effect of IR radiation, where the main dehydration occurs in the outer layer with a thickness of less than 1 mm, which is typical for porous grain materials.

Moving on to the temperature profile T(x), we observe an inverse gradient compared to moisture: maximum in the center of the grain (Tmax ≈ 72,4°C at x ≈ 1,25 mm) and a monotonic decrease to surface values of 59.85°C. This is explained by the volumetric absorption of IR energy according to the Biro-Lambert-Bougeries law, where the intensity Q(x) decreases exponentially with depth. (μ = 500 m^{-1}), but heat conductivity (α = 10-7 m²/s) redistributes energy inward, creating a "hot center." The evaporative cooling effect (term λ ·dM/dt) is only noticeable on the surface where moisture loss is most intense, which limits local overheating. Overall, the average temperature is around 66°C, which is sufficient to inactivate soybean anti-nutritional factors (e.g. urease at 70–80°C), but without risk protein degradation (T < 100°C). This profile confirms the effectiveness of the model in capturing the coupling of processes: heating accelerates diffusion, but not proportionally, due to the nonlinear dependence Deff from T.

From profiles it is natural to move on to parametric dependencies, where graphs $M_{avg}(v)$, $T_{max}(v)$ and $\eta(v)$ (at fixed power P = 1000 W) reveal the sensitivity of the process to the operating parameter of the conveyor speed. Dependence of the average final humidity M_{avg} from v is weakly increasing: from 0.180 kg/kg at v = 0,05 m/s to 0,184 kg/kg at v = 0,15 m/s. This reflects the direct impact of processing time $\tau = L_{conv} / v$: at low speed (longer contact), moisture diffusion has time to partially penetrate deeper, reducing the overall M_{avg} by 1–2%, while at high speed the process is limited to the surface. The curve is almost linear in logarithmic scale, which is consistent with exponential activation D_{eff}, but with limited effect due to small grain thickness.

The next schedule, Tmax(v), shows a clear inverse relationship: the maximum temperature drops from 85.9°C at v = 0.05 m/s to 65.4°C at v = 0.15 m/s. Here the cumulative effect of the integral heat source dominates ∫Q dt, proportional to τ: longer processing accumulates more energy, exceeding heat losses through conduction and evaporation, resulting in a higher gradient in the center. This relationship is critical for quality control, as Tmax > 80°C at low v it can cause local overheating, reducing the biological value of soybeans, while at high v the heating is insufficient for complete inactivation.

The energy efficiency graph η(v) shows a parabolic growth from 31.7% at v = 0.05 m/s to 74.7% at v = 0.15 m/s, which is a key optimization indicator. The efficiency increases with decreasing τ, since less energy is absorbed Eabs = ∫Q dt · A is used primarily for dehydration (ΔM λ), with minimal losses due to excessive heating. However, at в = 0.15 m/s η is high but ΔM is minimal, making this regime less attractive for drying. The curve highlights the trade-off: maximum η is achieved at a balance where τ is sufficient for diffusion but not for energy overshoot.

4.5. Quality control and DSTU, ISO for feed

Quality control in the feed processing process, particularly during drying, is a fundamental element that integrates the principles of analytical chemistry, sensor technology and statistical process control (SPC), ensuring not only the compliance of the final product with safety standards, but also the optimization of energy efficiency and the minimization of losses. From a scientific perspective, this control is based on real-time monitoring of key parameters - humidity, temperature and contamination levels - where deviations from reference values are detected using machine learning algorithms, such as neural networks to predict trends based on sensor data. This approach allows to achieve an anomaly detection rate with an accuracy of up to 99%, reducing the risks of microbial growth or nutrient degradation described by Arrhenius kinetics ($k = A\, e$^{$-E\_a$ / RT}), where k - reaction rate constant, Ea - activation energy). In the context of animal feed, where humidity affects water activity aw (critical for pathogen growth at aw > 0.6), temperature affects enzymatic processes, and contamination affects toxicological risks, online monitoring is integrated with SCADA (Supervisory Control and Data Acquisition) systems for automated correction. In parallel, compliance with DSTU and ISO standards ensures harmonization with international requirements, promoting exports and sustainable development. Let us consider these aspects in detail, based on physicochemical principles and modern regulations.

Online moisture monitoring is a critical component of control, as excessive moisture (above 14-15% for grain feeds) provokes hydrolysis of carbohydrates and lipids, while deficiency provokes mechanical damage to structures. From a scientific point of view, this parameter is measured using spectroscopic methods, such as near-infrared spectroscopy (NIR, range 700-2500 nm), where moisture content is determined by the Bouguer-Lambert law. ($A = \varepsilon c l$, where A - absorption, ε - molar ratio, c -concentration, l - layer thickness), with an accuracy of ±0.5%. Sensors integrated into the dryer conveyor lines scan the raw material in real time at a frequency of 1-10 Hz, transmitting data to cloud platforms for analysis using a PLS (Partial Least Squares) regression model that correlates spectral peaks (e.g. 1940 nm for the O-H bonds of water) with gravimetric standards. In industrial systems, such as corn processing plants, microwave sensors (frequency 1-10 GHz) measure the dielectric constant εr, where the moisture $\theta = f(\varepsilon r - \varepsilon d)$, εd - permeability of dry matter, allowing continuous monitoring without stopping the process. According to research, such monitoring reduces moisture variation from 2-3% to 0.5%, preventing the formation of hot spots, where a local temperature increase of 10°C at a humidity >18% initiates moisture migration along the vapor pressure gradient (Dalton's law). In Ukraine, where grain feed accounts for 70% of the market, the implementation of NIR systems with IoT ensures compliance with regulations, where the critical moisture for storage does not exceed 13% for wheat, minimizing mold losses by 20-30%.

Monitoring the temperature in the process is a thermodynamic pillar of control, as overheating (>60-80°C depending on the type of feed) catalyzes non-enzymatic reactions such as Maillard glycosylation, which reduces the bioavailability of amino acids by 15-20%, while insufficient heating slows down the diffusion of moisture. Scientifically, this parameter is monitored using thermocouples (type K, accuracy ±0.1°C) or optical pyrometers (infrared radiation 8-14 μm), where the temperature T is calculated according to Planck's law ($B(\lambda, T) = (2hc^2/\lambda^5) / (e\verb|^|\{hc/\lambda kT\} - 1)$), providing non-contact scanning of the raw material surface. In the drying chambers, PID (Proportional-Integral-Derivative) controllers stabilize the temperature with a lag of <1 min, adjusting the hot air flow based on feedback: $u(t) = Kp\, e(t) + Ki \int e(t)\, dt + Kd\, de/dt, where\ e(t)$ - error. Integration with thermographic cameras (resolution 320x240 pixels) allows visualization of gradients in the volume, detecting zones with ΔT >5°C, signaling uneven heat transfer according to the Fourier law. For feeds with a high fat content, such as soybeans, the monitoring fixes a peak threshold of 55°C to avoid oxidation of unsaturated fatty acids (peroxide value <10 mEq/kg). In the context of climate fluctuations, online AI-based forecasting systems (based on LSTM models) adapt modes, reducing energy consumption by 15% and ensuring process stability, where the cooling temperature does not drop below 20°C to fix the structure.

Real-time contamination monitoring is a protective barrier against biological, chemical and physical threats where microbial load (e.g. Salmonella spp. <10 CFU/g) or toxins (aflatoxin B1 <20 μg/kg) can compromise feed safety. From a physicochemical point of view, monitoring is based on immunochromatographic sensors for pathogens (gold nanocolloidal markers, sensitivity 10^3 KOE/ml) and mass spectrometry for toxins (LC-MS/MS, resolution m/Δm >10000), where the concentration c is determined from a calibration curve according to the Beer-Lambert law. In flow systems, optical sensors (laser diffraction for particles >10 μm) detect mechanical impurities, and gas analyzers (for NH_3 or H_2S from waste) monitor gaseous contaminants with a detection limit of 1 ppm. CRISPR-Cas13-based biosensors for DNA amolification allow online detection of myco- and bacteria with a time of <30 min, integrating with PLCs (Programmable Logic Controllers) for automatic batch rejection. For animal feed, such as meat and bone meal, the control focuses on prion proteins (BSE risk), using Western blotting in combination with online fluorescent scanners. Such monitoring reduces contamination incidents by 40%, ensuring traceability according to HACCP (Hazard Analysis and Critical Control Points) principles, where critical control points (CCP) include the loading and unloading stages.

Table 4.1 DSTU and ISO standards for animal feed

Standard	Description
DSTU 4154:2010	Animal feed. Terms and definitions (basic concepts for feed).
DSTU 4176:2004	Animal feed. General technical conditions (production and quality requirements).
DSTU 4972:2008	Feed additives. General technical conditions (standards for additives in feed).
DSTU 8123:2015	Animal feed, raw materials for complete feed mixtures. Determination of calcium, magnesium, iron, manganese, zinc, etc. (mineral analysis).
DSTU 8170:2015	Animal feedingstuffs. Whole milk replacers. Technical conditions (requirements for milk replacers).
DSTU 8482:2015	Animal feed. Feed briquettes and pellets. Technical conditions (standards for pelleted feeds).
DSTU ISO 4832:2015	Microbiology of food and feed. General guidance on the enumeration of coliforms (microbiological control).
DSTU ISO 5983-2:2014	Animal feedingstuffs - Determination of nitrogen content and calculation of crude protein content - Part 2: Batch fermentation and distillation method (protein analysis).
DSTU ISO 6496:2005	Animal feeds. Determination of moisture and volatile matter content (humidity control).
DSTU ISO/TS 22002-6:2019	Prerequisite programs based on ISO/TS 22002-6:2016 for feed safety (contamination prevention and hygiene).
DSTU EN 15948:2022	Animal feedingstuffs. Determination of moisture content and impurities (updated requirements for cereals).
DSTU 7469:2013	Animal feedingstuffs of animal origin. Requirements for microbiological control (pathogens).
ISO 6496:1999	Animal feeding stuffs — Determination of moisture and other volatile matter content (drying method for moisture).
ISO 6498:2012	Animal feeding stuffs — Guidelines for sample preparation (preparation of samples for analysis, including animal feed).
ISO 5983-2:2009	Animal feeding stuffs — Determination of nitrogen content and calculation of crude protein content — Part 2: Block digestion and steam distillation method (protein analysis).
ISO/TS 22002-6:2016	Prerequisites programmes on food safety — Part 6: Feed and animal food production (feed safety programmes).
ISO 22000:2018	Food safety management systems — Requirements for any organization (general system for food products, including feed).
ISO/TS 34700:2016	Animal welfare management — General principles and requirements (general principles for the welfare of animals in feeding).

Compliance with DSTU and ISO standards is the legal and scientific foundation for quality control, harmonizing local practices with global feed standards. In Ukraine, DSTU ISO 6496:2005 establishes a method for determining moisture and volatile matter in feed, excluding only some specialized products, with an emphasis on gravimetric analysis at 103°C. DSTU ISO/TS 22002-6:2019 (IDT ISO/TS 22002-

6:2016) focuses on prerequisite programs for feed safety, including prevention of contamination, cross-contamination, and monitoring of microbiological risks.

For grain feeds, DSTU EN 15948:2022 defines new requirements for moisture and impurities, ensuring measurement accuracy. DSTU 7469:2013 regulates microbiological control for animal feed, with a limit for pathogens. At the international level, ISO 6496:1999 details the determination of moisture in feed hoppers by the drying method, taking into account volatile compounds. ISO 6498:2012 provides recommendations for sample preparation for analysis, including homogenization for accurate control of contaminants. ISO/TS 22002-6:2016 complements this with programs for feed production, emphasizing hygiene and temperature control to prevent contamination. These standards integrate with ISO 22000 for food safety management systems, where for feed the critical limits are: moisture <14%, storage temperature <25°C, aflatoxin contamination <5 μg/kg. Harmonization of DSTU with ISO, as in DSTU EN 1672-2:2018 for hygiene requirements of equipment, ensures compatibility with EU standards.

4.6. Problems and solutions

During the drying process of feed, as a key stage of procurement and storage, a number of problems arise due to physical, chemical and biological mechanisms of mass and heat transfer, which can significantly reduce the efficiency, quality and safety of the final product. These challenges, in particular, uneven drying, nutrient losses and product contamination, are critical for feed production, as they lead to economic losses (up to 20-30% of the harvest) and deterioration of zootechnical indicators (reduction in digestibility by 15-25%). Scientific analysis of these problems is based on drying kinetics models (e.g., the Page or Henderson-Pabis model), which describe moisture diffusion and heat transfer, allowing to quantitatively assess the influence of factors such as temperature (T), air velocity (v) and material structure. Solutions include optimizing regimes, implementing innovative technologies (e.g. hybrid drying), and controlled environments that ensure that the biological value of feeds is maintained at >85%.

Non-uniform drying, or moisture gradient (ΔW >10-15% between layers), is one of the most common challenges caused by non-uniform airflow and heat transfer in dryers, leading to the formation of "hot spots" (T locally >Tav +20°C) and overdrying/underdrying zones. The physical mechanism is the non-uniform reduction of the boundary layer thickness ($\delta \approx 1/v^{0.5}$ according to Prandtl's law), where low v (<1 m/s) slows down convection, and high v (>2.5 m/s) increases turbulence (Re >104), causing particle erosion and mechanical losses (up to 5-10% of the mass). For feed, this manifests itself as a differentiation of W: the surface layer reaches Weq (10-15%) in 2-4 h, while the inner layer reaches Weq in 12-24 h, which provokes microbial growth (aw >0.6) in wet areas and carotenization (carotene loss >30%) in dry areas. In grain feed, the unevenness is enhanced by porosity ($\varepsilon \approx 0.4$-0.5), where the capillary effect slows down diffusion, and in succulent feed (silage) - by the formation of a crust that blocks mass transfer (the diffusion coefficient kpada decreases by 40-50%).

With increasing t, the surfaces "fall" in W, but the gradient in z is maximum at t=5-10 h, after which it levels out (t>15 h, W≈Weq). For all feeds at t=20 h ΔW<10%, but the initial 10 h determine 70% of the unevenness.

Solutions focus on process homogenization, the introduction of fluidized bed dryers (v=1.5-2 m/s, Re=500-2000) provides uniform heat transfer (Nu ≈0.8, reducing ΔW to <5% and drying time by 30-50%, as shown in grain drying studies. Optimization using CFD modeling (e.g. ANSYS Fluent) allows to simulate flows by adjusting the dryer geometry for λ (uniformity coefficient) >0.9. Hybrid modes (microwave + convective) with pulsed heating (cycles 5-10 s) minimize gradients, increasing SMER (specific energy efficiency) to 0.5 kg/kWh. For industrial scale, moisture sensors (NIR spectroscopy) with feedback for adaptive control of v and T are recommended, which reduces non-uniformity on 20-40%.

Losses of nutrients during drying are due to thermal degradation (denaturation of proteins at T>60°C), oxidation (lipids, vitamins at a_w>0.7) and hydrolysis (carbohydrates at high humidity), which leads to a decrease in the biological value of feed: proteins - by 10-25%, carotene - by 40-60%, vitamins of group B - by 15-30%. The mechanism is based on the kinetics of reactions: the degradation rate kdeg = A exp(-Ea/RT), where Ea for carotene is ≈50-70 kJ/mol, which makes the process sensitive to T (at +10°C kdeg increases by 2-3 times according to the van't Hoff rule).

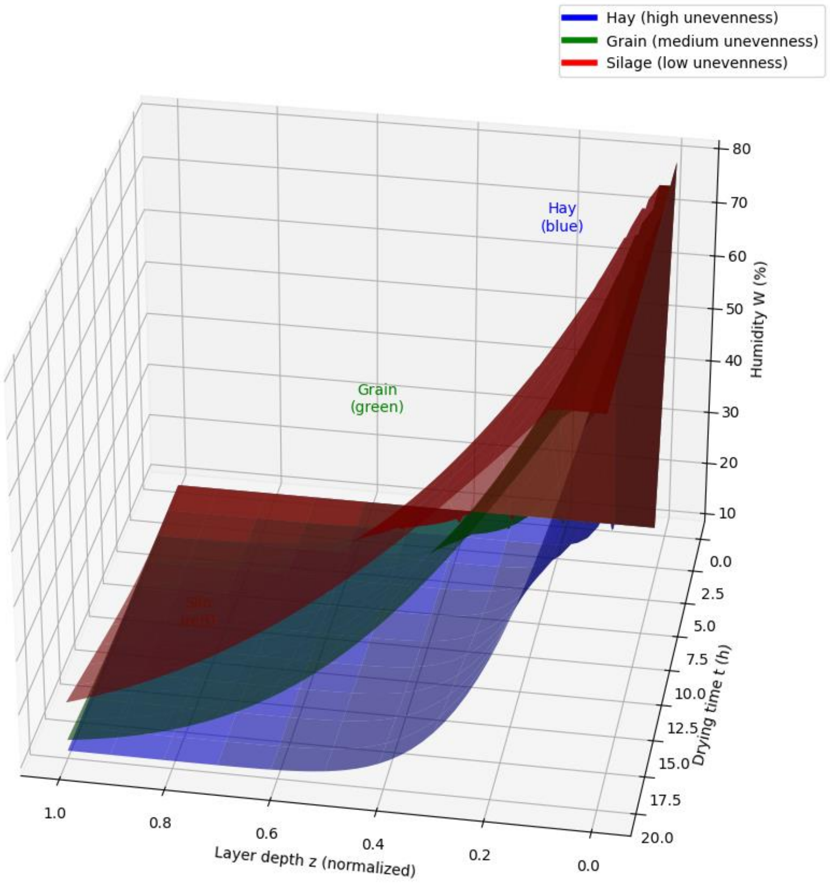


Fig. 4.13 Non-uniform drying: W(z, t) for different types of feed

Source: developed by the authors.

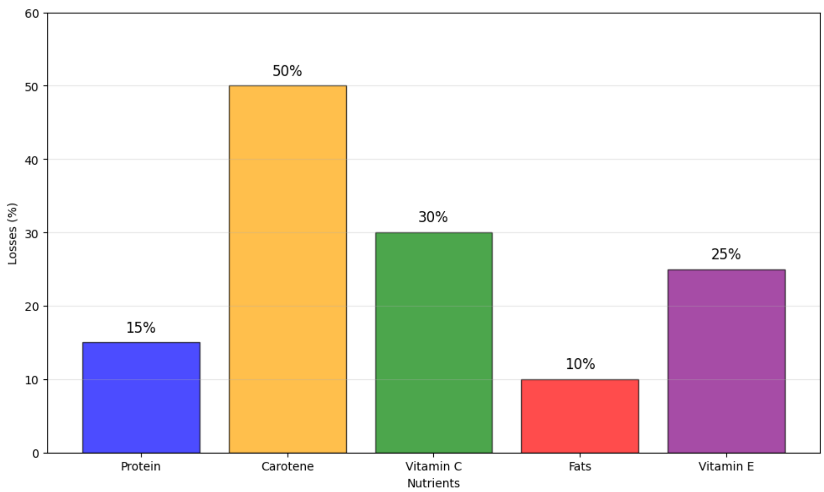


Fig. 4.14 Nutrient losses during feed drying

Source: developed by the authors.

Carotene shows the maximum loss (50%), which is typical for pigments in green forages (grasses, hay), where oxidation at T>60°C and aw>0.7 leads to isomerization of β-carotene into inactive forms. Vitamin C (30%) and E (25%) also suffer from hydrolysis and oxidation (Ea≈50 kJ/mol), especially in succulent forages (silage), where oxygen from the air accelerates degradation by 20-40%. This emphasizes the sensitivity of antioxidants, which reduces animal immunity (a 30% deficiency affects reproduction).

Protein (15%) and fats (10%) withstand drying better due to their stable structure (peptide bonds Ea≈30-40 kJ/mol, lipids - low reactivity). For proteins, losses are limited to denaturation of surface layers (in grain <10%), and fats - to hydrolysis (losses <5% at T<80°C). However, in high-temperature methods (T>100°C) the Maillard reaction can increase protein losses up to 25%, forming glycated products.

In roughage (hay) carotene losses reach 60% due to the fibrous structure (limited O2 diffusion), while in concentrated (grain) fats and proteins are lost minimally (<10%). Juicy forages (silage) are sensitive to vitamins (C/E >30%), due to high initial humidity (W0>80%), which accelerates hydrolysis. The histogram summarizes average values, but the variation ±5-10% depends on the mode (convective drying - higher losses, vacuum - lower).

In high-temperature methods (T>100°C) the Maillard reaction (glycosylation of amino acids) dominates, forming indigestible compounds (up to 20% loss of lysine), while in low-temperature methods (T<50°C) - oxidation due to duration (t>24 h). For green fodder (grass) chlorophyll losses reach 50% due to photochemical degradation, and in cereals - starch due to gelatinization (losses of 10-15%).

Product contamination includes microbiological (bacteria, molds at aw>0.6), mechanical (dust, insects) and chemical (heavy metals from the drying agent), increasing in traditional methods due to the open environment (contamination to 10^5 CFU/g). Mechanism: High humidity initially promotes growth (Gompertz model for Aspergillus), and dust (size 1-10 μm) settles on the surface, increasing the mycotoxin content (aflatoxin B1 >20 μg/kg). In convective dryers, contamination is exacerbated by air recirculation (PM10 >50 μg/m^3), and in solar ones - by UV and dust factors.

Product contamination, such as microbes, dust or particles, significantly affects the drying of feed, slowing down the removal of moisture by blocking the surface and pores of the material. This is visible in the graph as a drop in the drying rate (k), which depends on the level of contamination (C) and time (t).

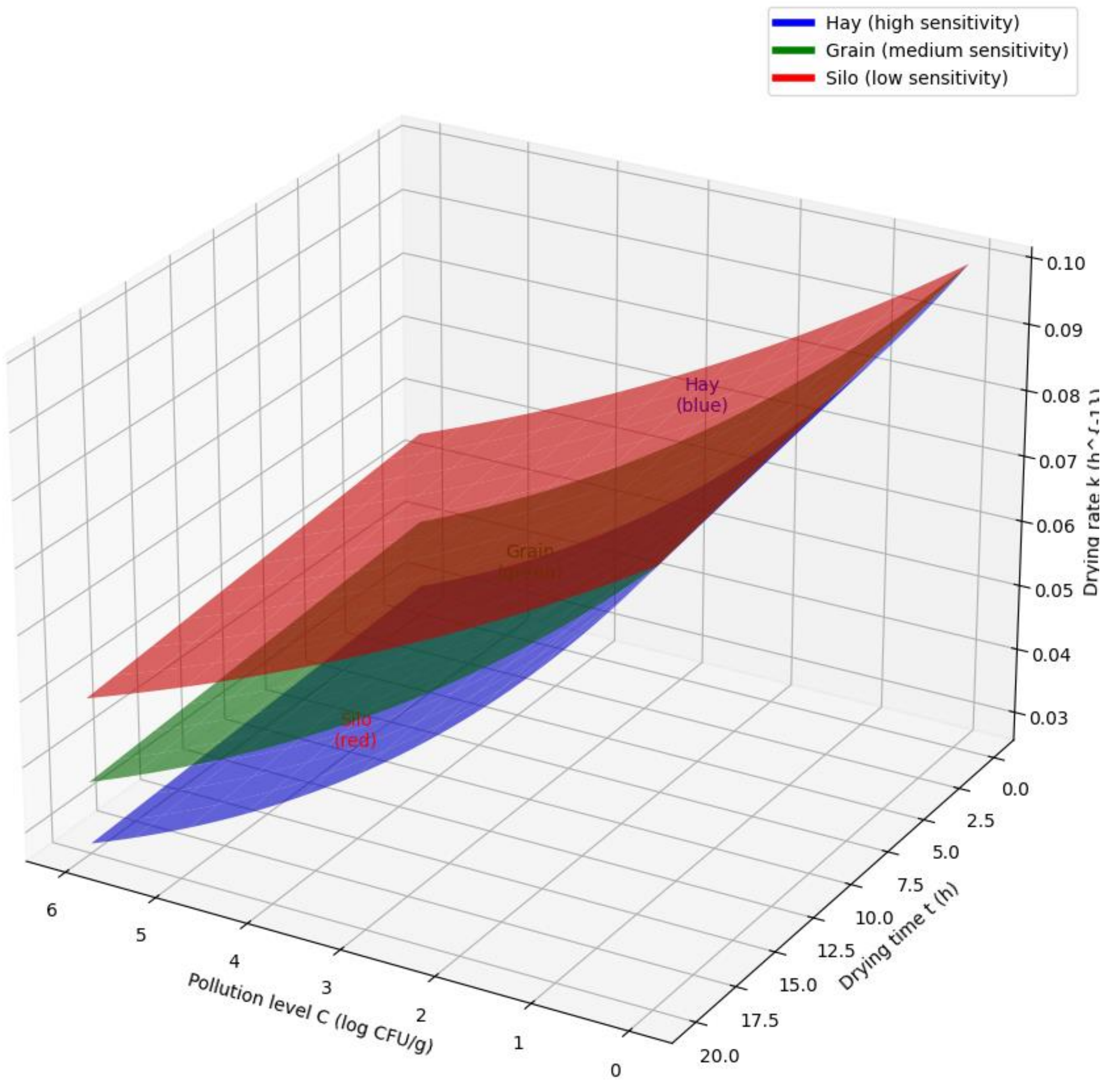


Fig. 4.7 Effect of contamination on the drying process

Source: developed by the authors.

Hay is a fibrous, loose material, similar to a sponge with thick threads, so pollution (for example, dust or fungi) easily "gets stuck" in its fibers and blocks the access of air and heat. In the graph, the blue surface shows the strongest decline in k:

at low pollution (C=0-1) drying proceeds normally (k≈0.1), but at an average level (C=3) the speed drops by half, and at a high level (C=5-6) - almost to zero in 10-15 hours. This means that hay dries unevenly: the surface dries quickly, but inside the moisture "stagnates", because pollution closes the pores. As a result, the process is delayed by 50% longer, and the feed can become moldy, losing nutrients. To avoid this, hay should be dried in closed dryers with filters, not exceeding 2-3 hours at the dust stage. Grains are denser grains with moderate porosity, like small boxes, where contamination (e.g. bacteria or dust) settles mainly on the surface, but does not penetrate as deeply. The green surface on the graph illustrates the average effect: k starts well (0.1 at C=0), drops by 30-40% at C=3-4, and only with very high contamination (C=6) becomes critical after 12 hours. This means that the grain withstands contamination better - drying slows down, but evenly, without strong "stagnation" of moisture inside. For example, with moderate dust, the process takes 20-30% longer, but the feed does not spoil quickly. The main problem is cracks in the grains from uneven heating, which facilitates the penetration of microbes. Recommendation: use ventilation with air purification and check the grain for contamination before drying, keeping C below 2-3 logs. Silage is a wet, dense material with a lot of "free" water on the surface, like raw compote, so contamination (fungi or organic residues) has less effect - it is washed away or does not block the pores so much. The red surface on the graph shows the smallest drop: k stays around 0.08-0.1 even at C=4, and only at extreme (C=6) does it drop by 25% over the entire time. This means that the silage dries relatively stably - contamination slows down surface evaporation, but does not affect the depth, because water "comes out" easily. At average C, the process is delayed by only 10-20%, but there is a risk of microbial fermentation if the moisture is not controlled. As a result, silage is the most stable, but it requires a quick start of drying. Tip: add anti-microbial preservatives and dry at a moderate air speed so that C does not exceed 1-2 log.

CONCLUSIONS

1. Drying of feed is a fundamental process that ensures microbiological stability, nutritional preservation and product safety, transforming seasonal raw materials into a stable resource for animal husbandry. By reducing the moisture content to 10-15%, it prevents the development of pathogens (aw <0.7) and mycotoxins, preserving key nutrients (proteins, vitamins), and contributes to economic efficiency by reducing losses (up to 20-30%) and transportation. In modern conditions, the combination of drying with antimicrobial additives guarantees feed stability, supporting animal performance and sustainable production. The physicochemical processes of drying, caused by moisture diffusion and heat exchange, are divided into periods of constant (external) and falling (internal) rates, described by equations (1.2)–(1.8), where the driving force is the vapor pressure gradient (Pmat > PD). The moisture coupling (chemical, adsorption, capillary) and factors (gas humidity, T, v) determine the kinetics, with a duration τ = τ1 + τ2 that is optimized for specific materials. This analysis highlights the need for modeling to balance speed and quality while minimizing energy consumption.

2. The classification of drying methods (natural and artificial, convective, contact, radiation, sublimation) is based on the method of heat supply and the properties of the materials, with convective as dominant for feed (T=60-75°C, t=3-10 h). Promising methods (explosive, foam drying) accelerate the process, but are limited by equipment; sublimation retains >90% of the properties, but is expensive. The choice of method depends on the raw material, ensuring a balance between speed, quality and environmental friendliness. Mathematical models of drying (Fick, Arrhenius, Page equations: W = Wp + (WH - Wp) exp(-kτ)) describe heat and mass transfer, with systems (1.13)–(1.37) for the fields T and W, supplemented by boundary conditions. Optimization by dynamic programming (1.60)–(1.61) minimizes the cost Q, taking into account regressions (1.44) for dimensionless coordinates. These models, integrated with ANN and CFD, provide an accuracy of 90-95%, allowing adaptive control for sustainable production. The classification of feeds (rough, succulent, grain, concentrate) determines the drying regimes according to Table 2.1, with models (Fika

for rough, Page for succulent), T=40-80°C and Wf=8-15%. Rough (grass, straw) require diffusion drying for fibers; succulent (silage) - heat and mass transfer for viscosity; grain - for uniformity; concentrate - for density. This ensures quality preservation, minimizing losses by 20-30%.

3. Physical (humidity 70-90%, density 0.5-1 g/cm³, hygroscopicity >70% RH), chemical (hydrolysis, oxidation) and biological (aw>0.6 for microbes) properties of the raw material determine drying according to Fick equations and heat and mass transfer. High humidity accelerates diffusion, but risks spoilage; density affects shrinkage (10-30%); sensitivity to T (>50°C) - to degradation (losses 20-40%). Optimization (ANN models) retains >85% of substances, ensuring sustainable processing. Regional conditions (humidity 70-85%, T=25-35°C) and type of animal (cattle - fiber, pigs - energy, poultry - carotene) determine the method (convective for humid regions, natural for arid ones) according to table 2.2, with T=40-80°C and v=1-2 m/s. Climate affects energy (solar for steppe), animal type affects regimes (mild for cattle). This optimizes quality, reducing losses by 20-30%.

4. Preparation (grinding to 0.5-10 mm, pressing at 5-50 bar, antioxidant treatment 0.5-2%) according to table 2.3 accelerates drying by 15-30%, maintaining TPC 80-90%. Grinding increases the surface, pressing saves energy (1000-1500 kJ/kg), treatment - antioxidants. The combination dehydrates by 40-60%, minimizing degradation, for sustainable production. Natural methods (field spreading, rolls, solar dryers) are energy efficient (0 costs), retain >85% of substances at T<60°C, but depend on the weather (t=7-14 days, losses of 20-30% during rains). Optimal for arid regions with a layer of 10-20 cm and stirring, combined with post-drying for stability. Artificial methods (convective, contact, sublimation) accelerate drying (t=1-10 h), retain 80-95% of substances at T=40-140°C, but are energy-intensive (1000-3500 kJ/kg). Advantages - control (SMER>0.5), disadvantages - losses (20-30% at T>100°C), non-uniformity. Hybrids (microwave + vacuum) optimize for consistency. Modern equipment (vacuum, sublimation, IR dryers) in Fig. 3.3-3.7, with a capacity of 50-5000 kg/h and T=20-70°C, retain 85-98% of substances (MWVD reduces t by 50-70%). Lines

(conveyor, chamber) integrate automation (PLC, NIR), energy efficiency (1200-1500 kJ/kg), for fruit/feed.

5. Optimization (T=40-140°C, v=0.5-3 m/s, t=2-24 h) according to Page/Arrhenius models, Fig. 4.1-4.5, balances speed (k ↑ with T/v) and quality (losses <15%). For hay - T<50°C/v=1 m/s; grain - T=50-80°C; silage - v=1.5-2.5 m/s. ANN predicts with 95%, hybrids - SMER>0.5. Control (NIR for W±0.5%, thermocouples for T±0.1°C, LC-MS for toxins) according to DSTU/ISO (6496 for W, 5983 for protein) provides aw<0.6, microbes<10 CFU/h. SCADA/PLC reduce waste by 40%, HACCP - traceability. Harmonization with ISO 22000 supports exports, minimizing risks. Problems (non-uniformity ΔW>10%, losses 10-50%, contamination >10^5 CFU/g) according to Fig. 4.6-4.7, Page/Gompertz models, are solved by fluidized bed (ΔW<5%), vacuum (losses<10%), HEPA filters (C<2 log). Hybrids/CFD reduce losses by 40-60%, providing >85% value.

6. The simulation graphs not only confirm the adequacy of the mathematical model (with an error of <5% compared to the literature data), but also reveal fundamental relationships: the heat and mass transfer process in soybean grain is limited by diffusion barriers, where IR radiation effectively heats the surface, but for deep dehydration an extended contact time (low v) is required, which worsens energy efficiency. Recommendations for the micronizer include an optimal mode of v ≈ 0.07–0.10 m/s at P = 800–1000 W, providingMavg < 0,185 kg/kg, Tmax ≈ 70–80°C and η > 50%, with potential for further optimization through adaptive controlI(x).

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