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EFFECT OF WATER-HEAT TREATMENT REGIMES ON DEHULLING AND POLISHING OF SPELT WHEAT

Abstract

The article examines the use of spelt and einkorn as hulled forms of wheat, their current distribution worldwide and in Ukraine, processing directions, and their place in the grain production structure. It is shown that einkorn and spelt remain niche crops but maintain stable demand in the food industry. The chemical composition of the grain is analyzed, demonstrating that a high protein content, significant proportion of insoluble dietary fiber, and starch structure determine the increased value of processed products, while simultaneously complicating the establishment of processing regimes. Particular attention is given to the floral husks, which are tightly fused with the kernel, making dehulling and polishing essential stages in grain processing. It is determined that using technological schemes and regimes developed for naked wheat does not ensure efficient processing of hulled grains and leads to increased endosperm losses and unstable quality of the final product. The study reviews the state of regulatory support for processing spelt and einkorn in Ukraine, highlighting the absence of clearly established requirements for grain quality and processing conditions for groats and cereal products. The lack of regulated parameters, including moisture content, hull adherence, and grain bulk density, complicates the prediction of yield and final product quality. The necessity of scientifically determining rational water-heat treatment regimes as a tool for controlling the physico-mechanical properties of the kernel is substantiated. The aim of the study was to investigate the effect of initial moisture content of spelt grain of the "Zorya Ukrainy" variety (harvests 2019-2023) on whole-kernel yield and ash content during dehulling and polishing. The results indicate that kernel yield depends on both moisture content and dehulling duration. Grain with initial moisture of 13 % gave the lowest kernel yield, ranging from 74,8 % at 120 s to 71,9 % at 600 s, reflecting accumulated mechanical damage in the kernel structure. Increasing moisture to 15 % increased kernel yield by 1,1-1,6 % depending on processing time, while at 17 % the increase was 1,7-2,4 %, indicating greater plasticity of the husk and endosperm and improved resistance of the kernel to mechanical damage. During polishing, a similar trend was observed. Grain with 13 % moisture showed rapid flour formation and a decrease in kernel yield from 96,0 % at 30 s to 85,8 % at 300 s, accompanied by a decrease in ash content from 1,55 % to 0,80 %, indicating intensive removal of the outer endosperm layers. Moisture of 15 % provided a more uniform dynamic, with kernel yield decreasing from 96,8 % at 30 s to 87,4 % at 300 s, and ash content reducing from 1,61 % to 0,86 %, reflecting increased kernel resistance to abrasive effects. Grain with 17 % moisture retained the highest kernel integrity, with yield ranging from 97,1 % at 30 s to 87,9 % at 300 s and ash content from 1,68 % to 0,87 %, demonstrating maximum mechanical resistance during processing. Analysis of the data allows determination of optimal spelt grain treatment regimes: for dehulling, moisture of 15-17 % combined with a duration of 120-240 s ensures high productivity with minimal kernel losses. For polishing, optimal conditions are moisture of 15-17 % for 180-210 s, whereas for drier grain (13 %), the duration should not exceed 120-150 s.

Keywords: spelt, hulled wheat, grain moisture, water-heat treatment, dehulling, polishing, whole-kernel yield, flour fraction, ash content, groat production.

Introduction

Spelt and einkorn are among the oldest cereal crops cultivated by humans at the dawn of agriculture. Their use is closely linked to the formation of the first settled communities and the transition from foraging to farming. Archaeological evidence indicates that various ancient wheat forms, including einkorn and spelt, were already grown 9-10 thousand years ago in the Fertile Crescent region of the modern Middle East. Einkorn is considered one of the earliest domesticated wheat forms, valued by early farmers for its ability to grow on poor soils and tolerate adverse environmental conditions. Its grains were tightly covered with husks, making threshing difficult, but these husks protected the grain from moisture, spoilage, and pests during storage, which made einkorn an important crop for communities without advanced storage methods. In ancient Middle Eastern states, einkorn was widely used to prepare porridges, flatbreads, and simple loaves. It was cultivated in Mesopotamia, Ancient Egypt, and Asia Minor. Hulled wheats with properties similar to einkorn and spelt played a significant role in human diets; bread made from such grains was dense, flavorful, and could be stored even in hot climates. Spelt appeared somewhat later, as a result of natural hybridization of different wheat forms. From the regions of the Near East, it gradually spread into Europe alongside human migrations and agricultural expansion. During the Bronze Age, spelt was well known in Central and Western Europe. It quickly adapted to cooler climates and less fertile soils, becoming an important crop in areas where other wheat types could not produce stable yields. In antiquity, both einkorn and spelt played a notable role in the agriculture of Greek and Roman civilizations. In Ancient Rome, spelt symbolized traditional farming and was used to prepare porridges and bread consumed daily. Einkorn was also used, but over time it was gradually replaced by more productive wheat varieties. Nevertheless, in mountainous and poorer regions, both crops remained important and practically irreplaceable for an extended period. During the Middle Ages, spelt became particularly widespread in Europe, especially in what is now Germany, Switzerland, France, and Northern Italy. For many peasant households, it became a primary cereal crop because it tolerated cold winters and was less susceptible to diseases. Einkorn gradually lost importance during this period, though it continued to be cultivated in certain regions, particularly in Eastern Europe and the Caucasus, as a traditional local crop. With the further development of agricultural technologies, there was a gradual transition to cultivating naked varieties of soft and durum wheat, which yielded higher harvests and were easier to process. Due to its difficult threshing and lower productivity, spelt and einkorn became less economically advantageous. In the 18th and 19th centuries, their cultivation areas sharply declined, and in some regions these crops nearly disappeared entirely. In the 20th century, amid intensive agricultural development, spelt and einkorn were largely sidelined in crop production. However, by the end of the century, interest in them began to gradually revive, driven by a reassessment of dietary traditions, increased attention to cereal diversity, and the search for alternatives to common modern wheat varieties [1-4].

Literary review

In the modern world, spelt and einkorn occupy a very limited, niche position within overall grain production. Compared to common wheat, the difference is striking, as global wheat production consistently reaches approximately 770-800 million tons annually. Against this background, the combined production volumes of spelt and einkorn appear insignificant, totaling only a few million tons, which is less than one percent of global wheat production. The largest share of contemporary spelt production is concentrated in Europe, which accounts for about 60-70 % of the world's total harvest of this crop. Germany leads in production, with an annual output of 80-100 thousand tons of spelt. By comparison, total wheat production in Germany exceeds 20 million tons, meaning spelt constitutes less than half a percent of the total. Significant, though still relatively small, quantities of spelt are produced in France, with an annual harvest of around 60-70 thousand tons, and in Switzerland, with 30-40 thousand tons per year. In Italy, Austria, and Belgium, spelt is grown in even smaller volumes, generally not exceeding 20-30 thousand tons annually per country. Einkorn is even less widespread in Europe. Its primary production occurs in Italy, where the annual harvest is estimated at 15-25 thousand tons. In France, Germany, and Central European countries, einkorn is grown on a much smaller scale, usually only a few thousand tons per year, serving mainly local needs and not playing a significant role in overall grain production. In Asia, spelt has almost no industrial significance, with cultivation limited to small areas in Turkey and parts of the Caucasus, yielding less than 10 thousand tons annually. In Iran and the South Caucasus, total einkorn production is estimated at approximately 20-30 thousand tons per year. In North America, spelt is primarily grown in the United States and Canada as a niche product. U.S. annual spelt production is about 40-50 thousand tons, whereas total wheat output exceeds 45 million tons. Canadian spelt production is even lower, typically not exceeding 10-15 thousand tons per year. Einkorn is produced in North America only in very limited amounts, usually a few thousand tons. In Australia, spelt production remains highly limited, estimated at around 10-15 thousand tons per year, while total wheat production exceeds 30 million tons, underscoring the niche status of spelt. Einkorn is virtually absent in Australia and does not hold any significant place in the structure of grain production [2,5-7].

In modern countries where spelt and einkorn are cultivated, their processing directions have developed under the influence of two main factors: preserved culinary traditions and interest from the contemporary food industry. Unlike common wheat, from which 550-640 million tons of grain are processed annually worldwide, mainly for milling and feed purposes, spelt and einkorn are used in more diverse ways but on a much smaller scale. The total global volume of spelt and einkorn grain entering processing is estimated at approximately 500-700 thousand tons per year, with about 60 % being spelt and 40 % einkorn. In Western and Central European countries, primarily Germany, Switzerland, Austria, and France, the main processing direction for spelt is flour production. In these countries, roughly half or slightly more of the harvested spelt is directed to milling, corresponding to approximately 150-200 thousand tons of spelt flour globally per year, with nearly half of this volume produced in Germany and France. The resulting flour is used for bread baking, pasta production, and traditional pastries. By contrast, flour from common wheat in these countries is produced in tens of millions of tons, clearly highlighting the niche character of spelt products. The second most important processing direction for spelt in Europe is the production of groats. Approximately one-fifth of spelt grain is processed into whole or crushed groats, corresponding globally to roughly 60-80 thousand tons of finished products per year. In Switzerland and southern regions of Germany, these products enjoy stable domestic demand and are consumed in significant quantities, whereas the use of common wheat as groats remains secondary. The production of spelt flakes is concentrated mainly in European Union countries and North America, accounting for about 10-15 % of spelt grain, or roughly 40-60 thousand tons per year worldwide. Spelt flakes are consumed either as a standalone breakfast product or as an ingredient in muesli and instant cereal mixes. Against the backdrop of total global cereal flake production, which exceeds 15 million tons per year and is primarily based on traditional cereals, spelt accounts for less than one percent. Instant products made from spelt occupy an even smaller share in its processing structure, estimated at 3-5 %, corresponding to 15-20 thousand tons per year globally. The main production of such products is concentrated in Germany, the United States, and Canada, targeting consumers with higher purchasing power. For comparison, the global market for instant wheat and other cereal groats exceeds 10 million tons per year [8-12].

Einkorn has a somewhat different processing structure compared to spelt. In Italy and Ethiopia, which are the main contemporary regions of its use, the production of groats predominates. In Italy, about half of the harvested einkorn is processed into groats, used for traditional dishes, amounting to approximately 10-15 thousand tons of finished products per year. In Ethiopia, the share of groat processing is even higher, reaching around 70 %, corresponding to 100-140 thousand tons of einkorn groats, which are almost entirely consumed on the domestic market. Flour from einkorn is produced in significantly smaller volumes than spelt flour. Globally, its annual production is estimated at roughly 50-70 thousand tons, representing about a quarter of total einkorn processing. The largest producers of this flour are Italy, France, and the United States, where it is used for specialized types of bread and pasta, but it does not have widespread consumption. The smallest segment in the processing of spelt and einkorn is the production of cereal bars and ready-to-eat breakfast products; however, this segment shows the fastest growth rate. Worldwide, it accounts for no more than 5 % of the grain from these cereals, approximately 25-35 thousand tons per year. The main processing countries are the United States, Canada, Germany, and France. Against the backdrop of total global production of cereal bars and breakfast products, which exceeds 50 million tons, the share of spelt and einkorn products remains almost negligible [13-16].

The chemical composition of einkorn and spelt developed over a very long period of their natural evolution and differs significantly from that of modern soft wheat. These differences concern not only the ratio of major nutrients but also the structure of the protein fraction and the content of biologically active compounds. Both crops belong to hulled wheat species, and this feature substantially influences their chemical composition. Einkorn and spelt are characterized by a higher protein content compared to most soft wheat varieties. In spelt grain, protein content typically ranges from 14 to 18 %, and under favorable growing conditions, it can exceed 19 %. Einkorn generally contains 13-17 % protein, often approaching the upper limit in traditional cultivation areas. For comparison, in soft wheat, average protein content usually does not exceed 10-13 %. Importantly, protein quality is as significant as quantity. The protein complex of einkorn and spelt has an increased proportion of water- and salt-soluble fractions and a somewhat lower share of fractions responsible for forming the gluten network. The amino acid composition of einkorn and spelt proteins is generally more balanced, with higher levels of lysine, threonine, and methionine than in soft wheat proteins. In spelt, lysine content is approximately 3.2-3.8 g per 100 g of protein, whereas in soft wheat it often does not exceed 2.8-3.0 g, which accounts for the higher biological value of proteins in these ancient wheat forms. Carbohydrates in einkorn and spelt are mainly represented by starch, comprising 55-65 % of the grain. In spelt, starch content is 58-63 %, and in einkorn 55-60 %, slightly lower than in soft wheat, where starch often exceeds 65-68 %. A notable feature is the structure of the starch. Einkorn, and to some extent spelt, has a higher proportion of amylose, reaching 28-30 %, which affects grain behavior and the texture of groats during cooking, resulting in denser, less sticky finished products. Simple sugar content in both grains is low, usually not exceeding 1,5-2,0 %, although the composition is somewhat more diverse due to the presence of maltose and small amounts of fructose. Dietary fiber is also important. Total fiber content in spelt averages 8-11 %, and in einkorn 9-12 %, significantly higher than in soft wheat. Insoluble fibers, particularly cellulose and hemicelluloses, dominate, but β-glucans and arabinoxylans are also present, strongly influencing the functional properties of processed products. The lipid fraction of einkorn and spelt shows both quantitative and qualitative differences. Total fat content usually ranges from 2,5-3,5 %, occasionally reaching 4 %, slightly higher than in soft wheat. Most lipids are concentrated in the germ and aleurone layer. The fatty acid profile is dominated by unsaturated fatty acids, primarily linoleic acid, which can constitute 50-55 % of total fatty acids. Oleic and palmitic acids also play significant roles, while stearic acid content is minor. The mineral composition of einkorn and spelt is characterized by elevated concentrations of both macro- and microelements. Grain ash content ranges from 1,8-2,3 %, higher than in soft wheat. Phosphorus, magnesium, potassium, and iron are particularly abundant. In spelt, magnesium content typically ranges from 120-150 mg per 100 g of grain, and in einkorn it can be even higher. Iron content usually ranges from 3,5-5,0 mg per 100 g, enhancing the mineral value of whole-grain products. Vitamins in einkorn and spelt are predominantly from the B group. The grain contains thiamine, riboflavin, niacin, and pyridoxine in amounts that generally exceed those in refined wheat flour. Niacin is particularly notable, reaching 6-7 mg per 100 g of whole spelt grain. Additionally, the germ contains tocopherols, which provide antioxidant properties to the lipid fraction and further enhance the nutritional value of processed products [17-20].

Formulation of the problem

Einkorn and spelt in Ukraine are represented as permanent niche cereal crops that are gradually gaining popularity due to the increasing interest in healthy and organic food. These crops are not part of the main food production system but maintain stable domestic demand and are mainly used for the production of bakery products, groats, pasta, and specialized food items. Einkorn annually provides between 12,000 and 25,000 tons of grain, while spelt yields 8,000-15,000 tons per year. These figures indicate relatively small cultivation volumes compared to traditional cereals, yet the crops occupy an important niche within the country’s agro-industrial complex. Over the past decade, the cultivation volumes of einkorn and spelt have remained relatively stable, reflecting limited sowing areas and the specific agronomic requirements of these crops. Einkorn accounts for a larger share of production, approximately 60-70 % of the total, while spelt constitutes 30-40 %. This distribution is explained by einkorn’s broader adaptation to different soil and climatic conditions and its traditional use in the Forest-Steppe and Polissya regions, where growing conditions are most favorable for stable yields. Spelt, by contrast, is more often cultivated in the Steppe and Forest-Steppe regions, where climatic conditions allow for high-quality grain with sufficient protein and gluten content. The production dynamics of these crops over the last decade show gradual growth with some fluctuations. In 2015, einkorn production was approximately 14,000 tons, and spelt 8,000 tons. In the following years, both crops showed an increasing trend: by 2017, einkorn production rose to 18,000 tons and spelt to 10,000 tons, reflecting expanded sowing areas and growing market demand. In 2020, einkorn production reached 23,000 tons and spelt 12,000 tons, indicating a stable strengthening of their position within niche cereals. By 2022, production

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was approximately 22,000 tons for einkorn and 13,000 tons for spelt [21-25].

In Ukraine, the breeding of einkorn and spelt is carried out by several main scientific centers that develop varieties for food use and grain production. The primary center is the V.Ya. Yuriev Institute of Plant Production of the National Academy of Agrarian Sciences of Ukraine, where the einkorn varieties Antares, Holikivska, Romanivska, and Yunika were created. Active work on spelt is conducted by the Bila Tserkva Experimental and Breeding Station of the Institute of Bioenergy Crops and Sugar Beets of NAAS, which developed the varieties Vyshyvanka bilotserkivska and Evrika. These varieties are oriented toward grain production and are distinguished by high protein and gluten content. Another scientific center is the All-Ukrainian Scientific Institute of Breeding (VNiS), which developed the varieties Europa and Zorya Ukrainy. These spelt varieties have high protein content and can provide consistent grain quality for the food industry, including flour and cereal production. Additionally, foreign spelt varieties registered in the state register are used in Ukraine, including Attergauer Dinkel (Austria) and MV Martongold (Hungary). Their introduction into the Ukrainian register occurs in cooperation with the scientific and breeding organizations of these countries, while domestic centers focus on adapting the varieties to Ukrainian climatic conditions and processing technologies. The einkorn and spelt varieties included in the Ukrainian state register have different physicochemical characteristics, which affects their processing applications. Einkorn is represented by the varieties Antares, Holikivska, Romanivska, and Yunika. The Antares variety, registered in 2021, has a thousand-kernel weight of 32,2-37,3 g, with a protein content ranging from 14,4 to 16,9%. Romanivska, registered in 2016, has a thousand-kernel weight of 32,6 g, protein content of 14,49%, gluten 29,5%, and grain bulk density of 742 g/l. Yunika, registered in 2020, has a thousand-kernel weight of 36,9-44 g and a protein content of 13-14,3%. Holikivska, registered in 2015, was developed at the V.Ya. Yuriev Institute of Plant Production and is intended for food use. The aforementioned einkorn varieties – Antares, Holikivska, Romanivska, and Yunika–are suitable for processing into cereals, flakes, and whole-grain flour, as they meet the requirements of the food industry and can be effectively used to produce various cereal products. Spelt in Ukraine is represented by the varieties Europa, Attergauer Dinkel, Vyshyvanka bilotserkivska, Evrika, Zollernspelz, Zorya Ukrainy, and MV Martongold. The Europa variety, registered in 2015, has a thousand-kernel weight of 45 g, protein content of 19%, gluten 45%, and grain bulk density of 765 g/l. Attergauer Dinkel, registered in 2019, has a thousand-kernel weight of 63,5-101 g, protein content 14,2-16,7%, gluten 29,9-31,9%. Vyshyvanka bilotserkivska, registered in 2020, has protein content 14,4-14,8%, gluten 29,1-30,2%. Evrika, also registered in 2020, has a thousand-kernel weight of 46,4-50,3 g, protein 13,8-15,6%, gluten 26,6-29,4%. Zollernspelz, registered in 2017, has a grain bulk density of 800 g/l and protein content 14,4%. Zorya Ukrainy, registered in 2012, has a thousand-kernel weight of 43,5-45 g and high protein content of 23-24%. MV Martongold, registered in 2022, has a thousand-kernel weight of 59,2-69,7 g, protein 15,7-16,8%, and gluten 32,3-35,2%. Regarding the use of spelt varieties in cereal production, all the listed varieties are capable of providing high-quality cereal products and can be used to produce various types of groats and cereal products, confirming their suitability for the food industry [21-25].

In Ukraine, the processing of hulled wheat forms into groats and cereal products lacks a systematic approach. Their use is limited to isolated production batches, primarily due to the absence of regulatory frameworks that would consider the specific properties of hulled grain and the particular requirements of its processing regimes. Unlike free-threshing wheat varieties, for which generally accepted quality standards and established processing schemes exist, hulled wheat does not have a clearly defined role within the current cereal processing system in Ukraine. The lack of regulation is evident at the stage of grain quality assessment. For einkorn and spelt, there are no mandatory indicators that would allow an objective determination of their suitability for groat production. Characteristics such as grain bulk density, thousand-kernel weight, hull adhesion, protein content, and gluten content do not have normative limits specifically defined for hulled wheat forms. Consequently, grains with varying properties enter production without a clear understanding of their technological behavior or the potential quality of the final product. Existing standards and processing regimes at enterprises are primarily oriented toward the processing of soft and hard free-threshing wheat and do not take into account the anatomical structure of hulled grain, in which floral husks are tightly fused with the kernel, significantly affecting all stages of the technological process. Processing hulled grain is characterized by the mandatory inclusion of dehulling operations and the subsequent separation of dehulling products, which, compared with free-threshing wheat processing, increases the duration of the process and raises its energy consumption. In modern production conditions, the processing of hulled wheat is often carried out without clearly justified and scientifically established dehulling regimes, which represents a key technological problem. Under such conditions, dehulling ceases to be a controlled process and becomes a compromise between the removal of husks and the preservation of the anatomical integrity of the kernel. Excessive dehulling intensity leads to mechanical damage of the aleurone layer and peripheral parts of the endosperm, where a significant portion of the grain's biologically valuable components are concentrated. This results in losses of protein, including fractions with high biological value. At the same time, there is an increased yield of fine flour and fragmented kernel particles, which complicates the subsequent sorting of dehulling products and reduces the overall yield of finished products. Conversely, insufficient dehulling intensity results in incomplete removal of husks, negatively affecting the quality of the final products, their culinary and consumer properties, and storage stability. The absence of standardized dehulling regimes complicates the reproducibility of processing results and renders product quality unstable even within a single enterprise. This limits the ability to predict product yield and composition, complicates technological control, and reduces the efficiency of grain raw material utilization.

Materials and methods

The aim of the study was to analyze the effect of the initial moisture content of spelt grain, cultivated in Ukraine, of the variety "Zorya Ukrainy" from the 2019-2023 harvests, on the yield of whole kernels during dehulling and polishing. To determine the influence of grain moisture on the efficiency of the dehulling process, cleaned spelt grain of the "Zorya Ukrainy" variety with an initial moisture content of 13 % was used. To assess the effect of initial moisture on the yield of whole kernels during dehulling and polishing, the grain was conditioned to moisture levels of 15 and 17 %, after which the samples were processed. To ensure uniform distribution of moisture throughout the grain mass, the grain was conditioned for 3-6 hours, which allowed equalization of moisture between the husks and the inner parts of the kernels.

The dehulling process was studied using a laboratory dehuller OlisLab 3100 – a laboratory-scale dehulling and polishing machine that allows replication of the mechanical effects typical of industrial dehulling. Grain samples with different moisture contents were dehulled for 120, 240, 360, 480, and 600 seconds, which made it possible to track changes in the intensity of husk separation depending on processing time and grain moisture. The mixture of dehulling products was directed to sorting in a laboratory sifter OlisLab 1100, where fine flour and small particles were removed. In the next stage, the dehulling products were processed in an aspiration column to separate the husks. This sequence of operations ensured clear separation of dehulling products and allowed an objective evaluation of dehulling efficiency. The technological efficiency of dehulling was determined by the total yield of whole kernels, which was used as a generalized indicator of process quality and the degree of kernel integrity preservation depending on grain moisture and dehulling duration.

To determine the effect of grain moisture on polishing efficiency, dehulled spelt kernels of the "Zorya Ukrainy" variety with an initial moisture content of 12 % were used; these were either dried to 10 % moisture or conditioned to 14 %. Conditioning lasted 1.5-3.0 hours, which contributed to equalization of moisture within the inner parts of the kernels. The polishing process was studied using the OlisLab 3100 laboratory dehuller-polisher, which replicates the mechanical conditions typical for industrial polishing. Grain samples with different moisture levels were polished for 30 to 300 seconds in 30-second intervals. After each polishing cycle, the product mixture was sorted using the OlisLab 1100 laboratory sifter, allowing separation of whole kernels, broken kernels, and flour. The efficiency of the technological process was evaluated based on the yield of whole kernels, the volume of by-products, and the ash content of the groats.

Results of the study and their discussion

The summarized results of the study on the effect of the initial moisture content of spelt grain on the yield of whole kernels during dehulling of the "Zorya Ukrainy" variety from the 2019-2023 harvests are presented in Table 1.

Table 1 - Effect of initial grain moisture on the yield of whole kernels during dehulling of spelt of the "Zorya Ukrainy" variety from the 2019-2023 harvests

Dehulling time, s	Moisture		
	13 %	**15 %**	**17 %**
120	74,8	75,9	76,5
240	73,9	75,2	75,8
360	73,0	74,6	75,1
480	72,3	74,0	74,6
600	71,9	73,5	74,3

The results of the study demonstrate the dependence of the whole-kernel yield of spelt of the "Zorya Ukrainy" variety on the initial moisture content of the grain and the duration of dehulling. The initial grain moisture was taken as 13 %, corresponding to the natural moisture after harvest. For this moisture level, the lowest whole-kernel yield was observed among the investigated conditions. At a dehulling duration of 120 s, the whole-kernel yield was 74,8 %, at 240 s – 73,9 %, at 360 s – 73,0 %, at 480 s – 72,3 %, and at 600 s – 71,9 %. The decrease in kernel yield over dehulling time was gradual, indicating a sequential accumulation of mechanical damage in the kernel structure. Increasing the grain moisture to 15 % led to higher whole-kernel yields across all processing durations. At 120 s, the yield was 75,9 %, at 240 s – 75,2 %, at 360 s – 74.6 %, at 480 s – 74.0 %, and at 600 s – 73,5 %. Comparison with the 13 % variant shows that higher moisture content contributed to better kernel integrity: the absolute difference in yield at 120 s was 1,1 %, and at 600 s – 1,6 %, reflecting reduced mechanical damage. During extended dehulling, kernel preservation remained higher compared with grain at initial moisture, and the overall decrease in whole-kernel yield under prolonged mechanical stress was less pronounced. For grain with 17 % moisture, the whole-kernel yield was maximal at all processing durations: 76,5 % at 120 s, 75,8 % at 240 s, 75,1 % at 360 s, 74,6 % at 480 s, and 74,3 % at 600 s. These values indicate increased kernel resistance to mechanical stress. With higher moisture, the husks showed greater deformability, allowing more effective separation from the kernel without significant cracking or fragmentation. The decline in whole-kernel yield over dehulling time was gradual, but the absolute reduction was the smallest among all moisture levels.

Analysis of dehulling duration revealed that for all moisture levels, there was a systematic decrease in whole-kernel yield. At 120 s, husk separation predominantly occurred at the early stages, while further increases in dehulling time intensified mechanical effects on the kernel, leading to microcracks and fragmentation. Gradual accumulation of damage was reflected in the uniform decrease in yield at each subsequent processing stage. Comparison across moisture levels shows a clear trend: higher moisture promotes higher whole-kernel yields at all dehulling durations. The difference between the 13 % and 15 % regimes ranged from 1,1 % to 1,6 %, depending on processing time, whereas the difference between 13 % and 17 % varied from 1,7 % to 2,4 %. The increasing

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difference with prolonged processing indicates a more pronounced effect of moisture on mechanical resistance under stronger abrasive forces. The decrease in whole-kernel yield over dehulling time was more pronounced for grain at 13 % moisture due to the higher brittleness of husks and surface kernel layers. For 15 % moisture, the decrease occurred more slowly, and for 17 % moisture, it was even less pronounced, demonstrating a direct relationship between kernel preservation and moisture content. These findings indicate that the physical and mechanical state of the grain determines its resistance to crushing and fragmentation during dehulling. The difference between moisture levels increased with dehulling duration. At 120 s, the yield difference between 13 % and 17 % moisture was 1,7 %, while at 360-600 s, it increased to 2,1-2,4 %, reflecting the cumulative effect of mechanical impact, which is more pronounced in drier grain. Grain at 13 % moisture loses kernel integrity more rapidly, whereas grain at 15-17 % moisture shows higher resistance during prolonged dehulling.

The dynamics of kernel yield reduction over processing time reflects the gradual accumulation of damage. For 13 % moisture, the absolute decrease in yield from 120 s to 600 s was 2,9 %, for 15 % – 2.4 %, and for 17 % – 2,2 %. The gradual reduction in yield during prolonged dehulling is associated with the progressive transition of husks and surface kernel layers into a state of microcracks and partial destruction. Higher moisture slows this process, reflecting greater mechanical resistance of the kernel and a reduced share of fragmented fractions. The whole-kernel yield of "Zorya Ukrainy" spelt at different moisture levels demonstrates a clear correlation between mechanical resistance and grain moisture. At 13 % moisture, yield losses occur more rapidly, reflecting increased brittleness and susceptibility to cracking. Increasing moisture to 15 % and 17 % gradually improves whole-kernel yield and reduces absolute losses during prolonged dehulling. With longer processing times, the differences between moisture levels become more pronounced, indicating a significant effect of the grain's physical and mechanical state on its behavior under dehulling. The results show that increasing grain moisture enhances whole-kernel yield at all stages of processing. At 13 % moisture, kernel losses occur more intensively, whereas higher moisture reduces mechanical damage intensity. For 15 % and 17 % moisture, whole-kernel yield gradually decreases with prolonged dehulling, but the total reduction is smaller, reflecting greater kernel resilience and fewer fragmented fractions. Over longer dehulling durations, a cumulative effect of mechanical damage is observed. For dry grain at 13 % moisture, this effect is more pronounced, while for grain at 15-17 % moisture, damage accumulates more slowly, demonstrating the improved ability of husks and surface kernel layers to absorb mechanical energy without cracking. The temporal dynamics of whole-kernel yield confirm the significant influence of grain moisture on kernel mechanical resistance during dehulling.

The optimal dehulling regime in terms of preserving kernel integrity is determined by the combination of processing duration and grain moisture. For grain with 15-17 % moisture, a processing time of 120-240 s is recommended, which allows effective separation of the husks without significant mechanical damage to the kernel. This regime minimizes whole-kernel losses while ensuring efficient dehulling and is technologically the most appropriate for maintaining a high-quality product during the processing of "Zorya Ukrainy" spelt.

In the next stage of the study, the influence of grain moisture on the efficiency of the polishing process was evaluated. The results of the study on the effect of initial grain moisture on the yield of whole kernels and by-products during polishing of "Zorya Ukrainy" spelt show a clear relationship between grain moisture, processing time, and the dynamics of main and by-product formation. Moisture affects the process through the physical and mechanical properties of the husks and endosperm, which determine the nature of kernel fragmentation under the action of abrasive elements of the polishing machine. For grain with initial moisture of 13 %, at the beginning of polishing (30 s), the whole-kernel yield was 96,0 %, with flour fraction at 4,0 %. Increasing the processing time to 60 s reduced kernel yield to 94,3 %, while the flour fraction increased to 5,7 %. At 90 s, the whole-kernel yield decreased to 92,9 %, with flour at 7,1 %. Extending polishing to 120, 150, 180, 210, 240, 270, and 300 s was accompanied by a gradual reduction in kernel yield to 85,8 %, while the flour fraction increased to 14,2 %. This decline is explained by the high brittleness of the surface layers of the endosperm in dry grain, causing cracks and intensive fragmentation of the kernel when interacting with abrasive elements. Accumulation of mechanical damage during prolonged polishing leads to a predictable increase in by-products, with losses progressively rising at longer durations, indicating the low resistance of 13 % moisture grain to abrasive action.

Grain samples with 15 % moisture exhibited a more uniform dynamic of kernel and flour yield during extended polishing. At 30 s, whole-kernel yield was 96,8 %, with flour at 3,2 %. At 60 s, the kernel yield was 95,4 %, flour 4,6 %, and at 90 s, kernel yield decreased to 94,5 % with flour increasing to 5,5 %. Extending the processing time to 120, 150, 180, 210, 240, 270, and 300 s resulted in a gradual decrease in kernel yield to 87,4 % and a corresponding increase in flour to 12.6 %. Higher moisture provides greater plasticity of the husks and endosperm, reducing kernel destruction during prolonged abrasive exposure and slowing the accumulation of fragmented fractions. The kernel yield dynamics indicate that 15 % moisture grain is more resistant to abrasive action and experiences lower product losses during extended polishing compared to 13 % moisture grain. Grain with 17 % moisture demonstrated the highest kernel resistance to mechanical stress from the polishing machine. At 30 s, the whole-kernel yield was 97,1 %, with flour at 2,9 %. At 60 s, the kernel yield was 96,2 %, flour 3,8 %, and at 90 s – 95.1 % and 4,9 %, respectively. Extending processing to 120, 150, 180, 210, 240, 270, and 300 s led to a gradual decline in kernel yield to 87,9 %, while the flour fraction increased to 12,1 %. Higher moisture ensures more elastic husks and kernels, allowing effective separation of husks without cracking or significant endosperm fragmentation, reducing by-product formation compared with 13 % and 15 % moisture grain.

Comparison of kernel and flour yield dynamics for all three moisture levels shows a consistent relationship between grain moisture, polishing duration, and the extent of by-product formation. Dry grain at 13 % moisture loses kernel integrity more quickly, reflected in a rapid increase in flour fraction during prolonged polishing. Increasing moisture to 15 % slows the rate of fragmented fraction formation, while at 17 % moisture, grain shows the slowest accumulation of flour due to greater plasticity of the husks and kernel and the ability of the endosperm to absorb abrasive energy without structural damage.

Polishing duration determines the pattern of mechanical damage accumulation in the kernel. In the initial stages (30-60 s), most of the abrasive energy is spent on removing husks and surface layers of the endosperm, whereas increasing the duration to 120-300 s intensifies the fragmentation of the internal part of the kernel.

The study of the effect of initial grain moisture on the ash content of polished "Zorya Ukrainy" spelt kernels demonstrates a direct relationship between the mechanical impact of the polishing machine's abrasive elements, the physical and mechanical properties of husks and endosperm, and the degree of mineral removal during processing. For grain at 13 % moisture, ash content at 30 s polishing was 1,55 %, decreasing to 1,43 % at 60 s. At 90 s it was 1,33 %, 120 s – 1,23 %, 150 s – 1,15 %, 180 s – 1,08 %, 210 s – 1,01 %, 240 s – 0,95 %, 270 s – 0,88 %, and 300 s - 0.80 %. This trend reflects intensive removal of the outer husk layers and fine endosperm, caused by the relatively low plasticity of husks and endosperm in dry grain, leading to more intensive surface structure disruption during prolonged polishing. For grain at 15 % moisture, initial ash content at 30 s was 1,61 %, decreasing to 1,49 % at 60 s, 1,39 % at 90 s, 1,30 % at 120 s, 1,22 % at 150 s, 1,15 % at 180 s, 1,08 % at 210 s, 1,01 % at 240 s, 0,94 % at 270 s, and 0,86 % at 300 s. Higher moisture ensures more uniform absorption of mechanical energy by the husks and endosperm, reducing the intensity of surface structure destruction and allowing the removal of outer layers without significantly affecting the kernel's structural integrity. This is reflected in the slower decrease in ash content compared with 13 % moisture grain, indicating better kernel resistance to the abrasive impact of the polishing machine. Grain with 17 % moisture exhibited the highest resistance to polishing. At 30 s, ash content was 1,68 %, 60 s – 1,56 %, 90 s – 1,46 %, 120 s – 1,36 %, 150 s – 1,29 %, 180 s – 1,21 %, 210 s – 1,13 %, 240 s – 1,05 %, 270 s – 0,97 %, and 300 s – 0,87 %. Higher moisture provides more elastic husks and kernels, allowing outer layers to be removed evenly without intensive endosperm destruction. In this case, the abrasive elements of the polishing machine primarily affect the husks and upper layers of the endosperm, reflected in the slower decrease in ash content compared with 13 % and 15 % moisture grain.

The dynamics of mineral removal during polishing demonstrate a direct relationship between processing duration and the degree of destruction of husks and the kernel's surface layers. For grain with 13 % moisture, 0,12-0,13 % of mineral components are removed during 30-60 s, 0,10-0,11 % during 90-120 s, and cumulative removal occurs at 0,07-0,08 % per interval during 150-300 s. Increasing moisture to 15 % slows the rate of mineral removal: 0,12 % is removed at 30-60 s, 0,10 % at 90-120 s, and 0,07-0,08 % at 150-300 s per interval, reflecting enhanced resistance of the kernel and husks. At 17 % moisture, mineral removal is even slower, with 0,12 % at 30-60 s, 0,10 % at 90-120 s, 0,07-0,08 % at 150-270 s, and 0,10 % at 300 s, demonstrating the kernel's maximum ability to resist abrasive action. Comparing ash content dynamics at different moisture levels shows a consistent decrease in the intensity of mineral removal as grain moisture increases. Dry grain undergoes more intensive removal of husks and upper endosperm layers due to low plasticity and increased brittleness of surface structures. Grain of medium moisture (15 %) exhibits more uniform removal with limited mineral losses, while grain at 17 % moisture retains a larger portion of mineral components even during prolonged polishing, reflecting its higher mechanical resistance. The optimal polishing regime is the treatment of grain with 15-17 % moisture for 180-210 s. This combination ensures a high yield of whole kernels, limits flour formation to 8-9,5 %, and minimizes mineral loss, maintaining sufficient kernel ash content. For grain at 13 % moisture, processing duration should be shorter, 120-150 s, to avoid excessive kernel fragmentation and loss of mineral components.

Conclusions

Spelt and emmer belong to the husked forms of wheat, whose processing differs significantly from that of hulled-free grain and requires a specialized technological approach. A key feature of this raw material is the strong adhesion of the kernel to the fruit and floral husks, which necessitates the inclusion of a dehulling stage. Processing schemes for emmer and spelt used in practice are often adaptations of procedures developed for wheat or barley; however, such adaptations are not always appropriate. The absence of standardized norms for grain quality parameters, degree of dehulling, and allowable losses complicates the standardization of final products. During polishing, increased abrasion of the kernel's surface layers occurs, leading to higher losses of nutrients and a reduction in the yield of the finished product.

The conducted research established that at 15-17 % moisture, an optimal balance is achieved between the intensity of husk removal and the preservation of kernel integrity. Under these conditions, dehulling for 120-240 s is technologically advisable, as it minimizes losses of whole kernels and ensures process stability. Polishing at this moisture for 180-210 s limits flour formation to 8-9,5 %. At the same time, it was found that reducing grain moisture to 13 % requires shortening the polishing duration to 120-150 s, since further mechanical exposure leads to intensive kernel fragmentation. The results indicate the necessity of differentiated selection of dehulling and polishing regimes depending on grain moisture and can be applied for scientifically grounded optimization of spelt processing technology to produce cereal products of stable quality.

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ВПЛИВ РЕЖИМІВ ВОДНОТЕПЛОВОЇ ОБРОБКИ НА ЛУЩЕННЯ І ШЛІФУВАННЯ СПЕЛЬТИ

Анотація

В статті розглянуто використання спельти і полби як плівчастих форм пшениці, їх сучасне поширення у світі та в Україні, напрями переробки і місце в структурі зернового виробництва. Показано, що полба і спельта зберігають нішевий характер, проте характеризуються стабільним попитом у харчовій промисловості. Проаналізовано хімічний склад зерна, визначено, що підвищений вміст білка, значна частка нерозчинних харчових волокон і будова крохмалю зумовлюють підвищену цінність продуктів переробки, але одночасно ускладнюють визначення технологічних режимів переробки. Особливу увагу приділено квітковим плівкам, які щільно зрощені з ядром і визначають необхідність застосування операцій лущення та шліфування як обов'язкових етапів переробки в крупи. Визначено, що використання технологічних схем і режимів, розроблених для голозерної пшениці, не забезпечує ефективної переробки плівчастого зерна та призводить до підвищених втрат ендосперму і нестабільної якості готової продукції. В роботі розглянуто стан нормативного забезпечення переробки спельти і полби в Україні та показано відсутність чітко встановлених вимог до якості зерна і режимів його переробки в крупи і круп`яні продукти. Відсутність регламентованих показників, зокрема щодо вологості, плівчастості, натури зерна, тощо ускладнює прогнозування виходу та якості готової продукції. Обґрунтовано необхідність наукового визначення раціональних режимів воднотеплової обробки як інструменту керування фізико-механічними властивостями зернівки. Метою дослідження було вивчення впливу початкової вологості зерна спельти сорту «Зоря України» (врожаїв 2019-2023 рр.) на вихід цілого ядра та зольність при лущенні і шліфуванні. Результати досліджень свідчать про залежність виходу ядра від вологості та тривалості лущення. Зерно з вихідною вологістю 13 % давало найнижчий вихід ядра – від 74,8 % при 120 с до 71,9 % при 600 с, із поступовим зниженням, що відображає накопичення механічних пошкоджень у структурі ядра. Збільшення вологості до 15 % підвищувало вихід ядра на 1,1-1,6 % залежно від тривалості обробки, а при 17 % – на 1,7-2,4 %, що свідчить про зростання пластичності оболонок і ендосперму та здатності ядра протистояти механічному руйнуванню. При шліфуванні спостерігалася аналогічна закономірність. Зерно з 13 % вологості демонструвало високу швидкість утворення борошенця та зниження виходу ядра від 96,0 % на 30 с до 85,8 % на 300 с, з одночасним зменшенням зольності від 1,55 % до 0,80 %, що свідчить про інтенсивне зняття верхніх шарів ендосперму. Збільшення вологості до 15 % забезпечувало більш рівномірну динаміку, вихід ядра з 96,8 % на 30 с до 87,4 % на 300 с, а зольність знижувалася від 1,61 % до 0,86 %, що свідчить про підвищену стійкість ядра до абразивного впливу. Зерно з 17 % вологості зберігало найвищу цілісність ядра, вихід коливався від 97,1 % при 30 с до 87,9 % при 300 с, зольність – від 1,68 % до 0,87 %, що відображає максимальну механічну стійкість при обробці. Аналіз отриманих даних дозволяє визначити оптимальні режими обробки зерна спельти: для лущення ефективним є поєднання вологості 15-17 % із тривалістю 120-240 с, що забезпечує високу продуктивність при мінімальних втратах ядра. Для шліфування оптимальними є обробки зерна з вологою 15-17 % протягом 180-210 с, тоді як для сухого зерна (13 %) тривалість не повинна перевищувати 120-150 с.

Ключові слова: спельта, плівчаста пшениця, початкова вологість зерна, воднотеплова обробка, лущення, шліфування, вихід цілого ядра, борошенце, зольність, круп'яне виробництво.

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