UDC 633.35:664
DOI: 10.15587/1729-4061.2024.313890

REVEALING THE EFFECT OF HYDROTHERMAL PROCESSING OF LEGUMES ON THE ACCUMULATION OF DRY MATTER IN AQUAFABA

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Legumes are an affordable source of vegetable protein, fiber, and vitamins, and due to their high nutritional and biological value, they are widely used in the nutrition of various categories of consumers. The main methods of processing legumes include hydromechanical and hydrothermal treatment, which is aimed at achieving culinary readiness of boiled legumes. Studying the parameters of the specified technological process for the accumulation of dry substances in aquafaba could make it possible to influence the composition and properties of this liquid, which would provide opportunities for its use in the food industry.

The influence of hydrothermal processing of leguminous grains on the accumulation of dry matter in aquafaba, as well as the kinetics of moisture content of various types of leguminous grains, have been experimentally investigated, which made it possible to determine the rational parameters of hydromechanical and hydrothermal processing of chickpeas, beans, peas, lentils, with the preparation of boiled leguminous grains and aquafaba.

It was determined that during hydromechanical processing intensive moisture absorption occurs in the first hours and reaches up to 80 % of the initial mass, after which the intensity of water absorption decreases somewhat. Rational technological parameters of hydrothermal processing of leguminous grains by two methods, basic (cooking at a temperature of 99±1 °C) and under pressure (cooking in a pressure cooker at a temperature of 120±1 °C) were established in the relationship "achieving the readiness of legumes – the content of dry substances in aquafaba". The use of the above-mentioned techniques for hydrothermal processing of leguminous grains make it possible to obtain the content of dry substances in aquafaba in the range of 2.8–4.8 % for cooking by the main technique and 3.9–7.0 % under pressure cooking conditions. To understand the processes regarding the influence of hydrothermal processing of legume grains on the accumulation of dry substances, the Peleg model was used.

The experimental data could be used to substantiate parameters for the technological process to produce foods based on legumes

Keywords: leguminous grains, dry matter, hydromechanical processing, hydrothermal processing, aquafaba, kinetics of moisture content

Received date 22.07.2024
Accepted date 10.10.2024
Published date 30.10.2024

How to Cite: *Hrynchenko, O., Dehtiar, V., Radchenko, A., Pak, A., Smetanska, I., Percevoy, F. (2024). Revealing the effect of hydrothermal processing of legumes on the accumulation of dry matter in aquafaba. Eastern-European Journal of Enterprise Technologies, 5 (11 (131)), 51–61. https://doi.org/10.15587/1729-4061.2024.313890*

1. Introduction

Legumes are an affordable source of vegetable protein, fiber, and vitamins, and owing to their high nutritional and biological value, they can enrich the consumer's diet.

In the technological process of the production of foods from legumes, two stages of their processing are distinguished in order to obtain a final product with high organoleptic indicators. The stage of hydromechanical processing involves soaking leguminous grains in order to swell the fibrous hydrocolloids and reduce the content of antinutrients. The stage of hydrothermal treatment, which is accompanied by a further change in the moisture content of leguminous grains, structural changes in proteins, starch, and carbohydrates of the fiber walls, aims to bring them to a state of culinary readiness and further use in the composition of various meals.

Global and local principles of responsible consumption and production determined new requirements for the implementation of technological processes. This fully applies to the technology of processing legumes into food products. During the hydrothermal treatment of legume grains, a liquid (broth) is formed, which was named aquafaba. Aquafaba is not a liquid to be disposed of, but a value-added product.

The transition of dry substances (proteins, starch polysaccharides, and others) to the cooking medium gives aquafaba new functional and technological properties. According to many studies, aquafaba exhibits emulsifying, foaming, thickening, and gelling properties, which allows it to be used in the technology of a wide range of food products.

2. Literature review and problem statement

Legumes are a product with high nutritional value, a source of vegetable protein, carbohydrates, and fiber. Earlier studies [1] summarized the chemical composition, biological features, and functional and technological properties of chickpeas, beans, peas, and lentils. The assumptions adopted in the cited work revealed the need to determine the influence of the parameters of the technological process on the production of aquafaba.

In addition to the unique chemical composition, legumes also have disadvantages, such as the presence of antinutrients and the long technological process of preparation. Hydromechanical processing of leguminous grains (soaking) is an important stage of the technological process because it makes it possible to increase the bioavailability of nutrients, reduce the duration of bringing the grains to culinary readiness, and reduce the content of antinutrients.

Work [2] investigated the liquid after hydromechanical processing of chickpeas, beans, green lentils, yellow split peas, and yellow soybeans. It was shown that water-soluble nutrients accumulate in the liquid. which have functional and technological properties. This allows the liquid to be used in gluten-free bread technology. At the same time, a high concentration of saponins and phenols was found in the composition of the liquid. Although they show emulsifying and foaming ability, they are anti-nutrients. This is a limitation regarding the wide use of liquid after hydromechanical processing of legumes in food technology.

During the hydrothermal treatment of legume grains, the carbohydrates of cell walls and starch swell, the transition of protopectin into pectin, the destruction of cell walls, the pasteurization of starch grains, and the denaturation of proteins occur. Water-soluble nutrients diffuse into the cooking medium, which insignificantly reduces the nutritional value of legumes. Due to the formation of the existing functional and technological properties of the liquid after cooking legumes, it was turned into a semi-finished food product and received the name aquafaba. The traditional way of cooking legumes, namely in a plate dish at 99±1 °C or under pressure at 120±1 °C, affects the total duration of bringing legumes to culinary readiness. In the case of shortening the cooking time of legumes, preference is given to cooking under pressure. Paper [3] compared the influence of the traditional cooking method and under pressure on the content of antinutrients in three varieties of beans. It was found that a more effective reduction of antinutrients occurs with the traditional cooking method. However, the study does not take into account other important aspects, in particular, the preservation of useful trace elements. For example, the authors of work [4] determined that with the traditional cooking method, Zn and Mg from the legume grains pass into the cooking medium, and with pressure cooking, they are stored directly in the legume. However, the available experimental data are focused exclusively on the final product, i.e., boiled legumes. This limits the understanding of the influence of technological parameters on the accumulation of dry substances in aquafaba, which is why additional research is necessary.

The issue of the influence of acidic and alkaline environments, sodium chloride on the duration of hydrothermal processing of legumes and the accumulation of dry substances in aquafaba remains a debatable issue. In [5], it is stated that the acidic environment of an aqueous solution increases the duration of heat treatment because acids compact pectin, making cell walls resistant to liquid absorption. This slows down the hydration and pasteurization of starch. In work [6] it is stated that sodium hydrogen carbonate and citric acid reduce the content of potassium and phosphorus in boiled leguminous grains. These factors may have a significant impact not only on boiled legumes but also on aquafaba, since the composition and properties of the liquid change after heat treatment, but these processes have not been investigated.

In [7], it is described that during cooking of legumes with sodium bicarbonate, the shell is damaged. This shortens the cooking time because sodium hydrogen carbonate affects the leaching of polysaccharides and proteins, the dissolution of pectin substances, namely calcium and magnesium pectates, which are included in the seed coat. However, legumes cooked in an aqueous solution of sodium hydrogen carbonate and the liquid after their cooking acquire a specific taste, dark coloration that occurs due to the Maillard reaction.

The cited research results [8] show that the addition of sodium chloride at the beginning of cooking increases the temperature of the liquid, which causes a higher degree of thermal dissociation of the bound molecules in legumes. The purpose of the research was to determine the influence of technological parameters of the preparation of boiled legumes on the content of phenolic acids and their antioxidant properties, which limits the application of experimental data.

At the same time, it was determined in [9] that a high concentration of sodium chloride has a negative effect on the osmosis process, which slows down the hydrothermal treatment. However, in thee work, there is no comparative analysis between different types of legumes, and the study was conducted for Chinese cowpea, after 1 and 12 months of storage. This reduces the possibility of applying the results to other types of legumes since their characteristics may differ significantly.

According to [10], during the hydrothermal treatment of legumes, sodium ions, which are part of sodium bicarbonate, can take part in an ion-exchange reaction, as a result of which calcium bridges are broken. As a result, the cell walls of legumes soften. As a result of the ion exchange reaction, sodium ions are replaced by calcium ions, which increases the water-absorbing and water-holding capacity. Accordingly, the addition of sodium ions changes the structure of the cell walls of legumes, which theoretically affects the accumulation of dry substances in aquafaba, but there are no experimental data regarding this assumption.

Due to the fact that water-soluble substances such as proteins, saponins, and polysaccharides that are part of legume grains diffuse into aquafaba, it is predicted that aquafaba has significant potential as a vegetarian alternative to egg white. Due to its emulsifying, foaming, thickening, gelling properties, aquafaba can be used to produce products with an emulsion texture.

In work [11], the content of dry substances in aquafaba from chickpeas during cooking in a pressure cooker at a temperature of 115–118 °C for 30 minutes at a hydro module of 1:2 was investigated, after which the chickpeas were left in aquafaba to cool for 6 hours. It was established that total soluble solid substances in chickpea aquafaba was 6.3±0.2 %. The disadvantage of the study is the long process of cooling aquafaba in a pressure cooker, which is not advisable for industrial production. This calls into question the parameterized possibility of obtaining aquafaba by the specified technology.

Work [12] investigated and compared liquids obtained after cooking meat, vegetables, chickpeas, and canned chickpeas, in particular the content of dry substances, protein, foaming and emulsifying properties. It has been established that only aquafaba from boiled or canned chickpeas exhibits properties similar to egg white. This was achieved by pre-soaking the chickpeas in the ratio of 300 g of chickpeas in 2 liters of water with the addition of 6 g of salt for 12 hours, after which the legumes were cooked in a pressure cooker for 35 minutes, at 100 kPa at a hydro module of 1:2. Aquafaba obtained by the specified technology has a total solids content of 5.84±0.08 %, and canned – 6.24±0.05 %. The study of aquafaba obtained from canned legumes provides only a general idea of its properties because experimental data will have high variability depending on the manufacturer and the specificity of technology.

In work [13], the total solids content in chickpea aquafaba soaked at a temperature of 40 °C for 2 hours was investigated. Rehydrated chickpeas were cooked from 15 to 60 minutes at different hydro modules in a pressure cooker. So, the minimum total solids content was 3.5±0.4 %, with a seed to water ratio of 2:3 (w/v) and 15 minutes of cooking. The highest dry matter content was 15.0±1.0 % at a hydro module of 1:4 and boiled in water for 60 minutes. However, with a lower hydro module of 1:2 and 60 minutes of cooking, the dry matter content was 11.3±0.5 %, which casts doubt on the obtained experimental data.

In [14], the total soluble solid, foaming ability of aquafaba from chickpeas was investigated to determine the possibility of its use as a substitute for egg proteins in the technology of cupcakes. The authors indicated that aquafaba was obtained by soaking chickpeas for 10 hours. The rehydrated chickpeas were boiled for 40 minutes at a hydro module of 1:4, after the cooking was finished, the aquafaba was drained. Aquafaba was characterized by total soluble solid was 5.2±0.1 %. However, it was possible to achieve similar properties to egg white only by changing the pH, adding xanthan gum and sodium chloride.

In [15], the technology for obtaining aquafaba from chickpeas is indicated as a standard for a standardized process. Aquafaba was obtained as follows: the prepared chickpeas were soaked for 8 hours at a temperature of 4 °C in deionized water, after which the rehydrated chickpeas were boiled for 20 minutes at a hydro module of 2:3 and stored in aquafaba for 24 hours. It was established that the total solids content was 10.24±0.04 %. The authors chose hydromechanical processing of legumes at a temperature of 4 °C but this temperature is achieved using refrigeration equipment, which is not rational for industrial production.

In the reviewed works [11–15], a technique for obtaining and the content of dry substances in aquafaba differ from each other, which indicates the absence of a standardized technological process for its production. In most of these papers, the technological process of obtaining aquafaba from chickpeas using a pressure cooker was investigated.

It has been analytically proven that due to the influence of various factors on the change in the moisture content of leguminous grains and the accumulation of dry substances in aquafaba, it is appropriate to use physical-mathematical empirical models. The application of Peleg's model for approximating the kinetics of moisture content in leguminous grains showed that the speed of the specified process differs in published works in connection with different growing regions, biological diversity of leguminous plants, different physical characteristics, parameters of hydromechanical processing. For example, work [16] revealed an excellent content of nutrients, especially protein (16.3–26.2 %), Fe (44.1–76.7 mg/kg), and Zn (36.3–56.2 mg/kg) among 280 chickpea samples that were studied by the authors for two years. Considering the variety of botanical varieties, morphological structure, chemical composition and different geographical and climatic conditions of growing legumes, the scientific literature is limited to generalized and systematized parameters related to their processing. This makes it difficult to determine the influence of these parameters on the properties of aquafaba. Therefore, despite the availability of numerous scientific publications, questions remain regarding the determination of rational parameters for the technological process of obtaining not only boiled legumes but also aquafaba with the optimal content of water-soluble nutrients. This makes it necessary to conduct a study to determine the rational parameters for the hydromechanical and hydrothermal processing of legumes in terms of the accumulation of dry substances in aquafaba.

3. The aim and objectives of the study

The purpose of our study is to determine the effect of hydrothermal treatment of leguminous grains on the accumulation of dry matter in aquafaba. This will make it possible to determine rational processing parameters for leguminous and aquafaba grains, which will allow them to be used in food production technologies.

To achieve the goal, the following tasks are set:

– to investigate the change in the moisture content of chickpeas, beans, peas, and lentils during hydromechanical processing;

– to investigate the content of dry substances in aquafaba during hydromechanical processing depending on the ratio of leguminous grain:water, temperature of the cooking medium;

– to determine the influence of citric acid and sodium bicarbonate on the accumulation of dry substances in aquafaba during hydrothermal treatment.

4. The study materials and methods

The object of research is the technological parameters for obtaining aquafaba, which is a liquid from the cooking of leguminous grains, namely, the parameters of hydromechanical and hydrothermal processing of raw materials.

The research hypothesis assumes that the accumulation of dry matter in aquafaba depends on the type of legumes and the parameters of technological process of bringing them to culinary readiness. In connection with this, it is assumed that research and determination of rational parameters for the hydromechanical and hydrothermal processing of leguminous grains will make it possible to obtain aquafaba with a predefined content of dry substances and specified functional and technological properties.

The study of the hydration behavior of leguminous grains is necessary for the predicted course of the technological process for obtaining a finished product with specified properties.

The initial raw material for the study was the 2023 harvest of legumes grown in a moderately continental climate. We used the following: chickpeas (type "Kabuli", variety "Rozanna", growing region – Poltava region, Ukraine), white beans (variety "Mavka", growing region – Kyiv region, Ukraine), common yellow split peas (variety "Motto", growing region – Odesa region, Ukraine), red lentils (Kanadka variety, growing region – Odesa region, Ukraine). During the study, citric acid and sodium bicarbonate were used, which corresponded to the current regulatory documents.

Legume grains were sorted, damaged seeds were removed, leaving visually the same size and shape to exclude the influence of these parameters on the course of the experiment.

Hydromechanical processing was carried out as follows. Prepared legume grains were soaked in drinking water for 14 hours at a hydro modulus of 1:1.5 to 1:3.0 at t=18.0±0.5 °C. The current mass of system water was determined every 30 minutes. Swelling of leguminous grains occurred until the change in mass of the samples stopped.

Hydrothermal treatment of rehydrated legume grains was carried out in two ways. The first hydrothermal processing technique (the main technique) involves the use of flatware and a cooking surface, cooking legumes at a hydro module of 1:1.5, 1:2.5 for chickpeas, beans, peas, 1:2.0, 1:3.0 for lentils for 40–80 min at temperature 99±1 °C. The second hydrothermal treatment technique involves cooking legumes under pressure using a pressure cooker at a hydro module of 1:1.5 for chickpeas, beans, peas, 1:2 for lentils for 5–40 min at a temperature of 120±1 °C.

A separate study was conducted under the condition of adding citric acid or sodium bicarbonate to the aqueous solution for the hydrothermal treatment of leguminous grains, carried out by the first technique.

The moisture content of leguminous grains was determined according to the formula [17]:

$$w=\frac{m_w}{m_{s.s.}}\cdot 100\,\%, \tag{1}$$

where w is the current moisture content, %; m_w is the current mass of system water held by leguminous grains, kg; $m_{s.s.}$ (solid substances) – mass of dry substances of leguminous grains, kg.

Mass of dry substances $m_{s.s.}$ was determined by drying 1 g of a sample of crushed raw materials in a Radwag MA 50/C/1 moisture analyzer at a temperature of 105 °C to a constant mass [18].

Taking into account the use of improved approaches to the methods for analyzing the moisture content of leguminous grains, the concept of "system water" was used, the essence of which is covered in paper [19].

The current mass of system water m_w was determined as the difference between the value of the current mass of legume grains $m_{r.m.}$ (raw material) and the mass of dry substances that leguminous grains contain:

$$m_w=m_{r.m.}-m_{s.s.}. \tag{2}$$

The obtained experimental points were fitted to a function of the form:

$$f_{wi}(\tau)=a_{wi}-e^{b_{wi}+c_{wi}\cdot\tau}, \tag{3}$$

where a_{wi}, b_{wi}, c_{wi} are approximation coefficients.

With the application of the resulting mathematical model (3), for each type of leguminous grain, a data array was built, which contained the value of the current moisture content of the raw material for different durations of its hydromechanical processing from the range of 0...840 min. The discreteness of the processing duration values, for which the current moisture content values were calculated, was 10 minutes. A sub-array was selected from the initial array, starting with the value of the moisture content, which corresponds to the maximum duration of hydromechanical processing. Further, by adding points from the main array to the subarray one by one in the reverse order, the values of the current moisture content from the obtained subarray were approximated. At the same time, the approximation function was a linear function of the form:

$$f(\tau)=a+b\cdot\tau, \tag{4}$$

where a and b are approximation coefficients.

The content of dry substances in aqueous solutions (aquafaba) was studied by the refractometric method on a URL-1 model refractometer in accordance with DSTU 8402:2015.

The hydration behavior of leguminous grains in the technological flow is not fully explained by the kinetics of moisture content but includes swelling processes, structural changes of fibrous hydrocolloids. Therefore, it is advisable to use a physical-mathematical or empirical model for a better understanding of these processes when determining the rational parameters for the technological process of obtaining boiled beans and aquafaba. From the empirical models, it is possible to use the Weibull, Peleg, first-order equation models. Based on the ease of use, the possibility of optimization and modeling of the technological process, understanding the regularity of changes in the hydration behavior of legumes, the Peleg model was chosen.

Approximation of experimental data, which was the content of dry substances in aquafaba, was carried out using the physical and mathematical model of Peleg [20]. For Peleg's model, the mathematical notation takes the form:

$$C(\tau)=\frac{\tau}{K_1+K_2\cdot\tau}, \tag{5}$$

where $C(t)$ is the content of dry substances in aquafaba, %; t – duration of hydrothermal treatment, min.; K_1 and K_2 are Peleg's constants, %/min. and %, respectively.

5. Results of investigating the influence of hydromechanical and hydrothermal processing of legumes on the content of dry substances in aquafaba

5. 1. Investigating changes in the moisture content of chickpeas, beans, peas, and lentils during hydromechanical processing

The kinetics of the moisture content of the studied samples of leguminous grains, which is a change in the moisture content of the raw material w over the time of its watering τ, are shown in Fig. 1. The correlation coefficient for the obtained approximation functions was in the range from 0.96 to 0.98.

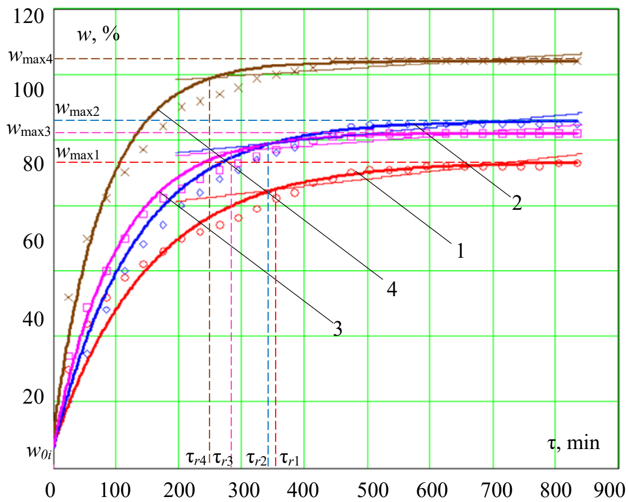

Fig. 1. Kinetics of moisture content during hydromechanical processing of legume grains: 1 — chickpea; 2 — beans; 3 — peas; 4 — lentils (t=18.0±0.5 °C)

The initial moisture content of all types of legume grains was within 8.0...11.9 %.

The obtained kinetics of moisture content have the same character. The current moisture content increases monotonically from the initial value of the moisture content of the sample w_{0i} as the duration of watering of the studied samples increases. With an increase in the duration of irrigation relative to the specified values, the moisture content asymptotically tends to the maximum value, which has a different $w_{\max i}$ value for different samples.

Given this and the analytical form of approximation function (3), one can assume that the initial value of the moisture content of the ith sample w_{0i} corresponds to the approximation coefficient a_{wi}, and the coefficient b_{wi} corresponds to the maximum value of the moisture content of the ith sample $w_{\max i}$. Based on this, it is possible to obtain an analytical expression of the kinetics of moisture content (4).

Thus, taking into account the form of approximation function (3) and comparing the values of the approximation coefficients (a_{wi}, b_{wi}, c_{wi}) and the values of the initial (w_{0i}) and final moisture content ($w_{\max i}$) of the raw material, the following analytical expression is proposed for the kinetics of the moisture content:

$$w_i(\tau) = w_{\max i} - e^{w_{0i} + c_{wi}\cdot\tau}, \qquad (6)$$

where w_i is the current moisture content, per cent, %; w_{0i} – initial moisture content of raw material, % g; $w_{\max i}$ – final moisture content of raw materials after hydromechanical processing, %; i=1, 2, 3, 4, depending on the sample number: i=1 – chickpea; i=2 – beans; i=3 – peas; i=4 – lentils.

As for the approximation coefficient c_{wi}, its dimensionality, based on the exponent power indicator (6), corresponds to the change in moisture content over time – %/min. That is, the dimensionality of this coefficient corresponds to the rate of change in moisture content due to the sample absorbing the wetting liquid in the medium of which it is located. According to Fick's law, this value is determined by temperature and water absorption coefficient.

The values of the coefficients included in the constructed physical-mathematical model for various legume grains are given in Table 1.

Table 1

Coefficients of the physical-mathematical model of moisture content kinetics during hydromechanical processing

The name of legumes	Initial value of moisture content, w_0, %	Maximum value of moisture content, $w_{\max}$, %	Approximation coefficient, c_w 10^3, %/min
Chickpeas	4.5	93.4	6.536
Bean	4.6	106.0	7.746
Pea	4.6	102.2	9.813
Lentil	4.4	86.2	6.658

Based on the type of moisture content kinetics (Fig. 1) and the data in Table 1, the moisture content asymptotically tends to the maximum value. That is, there is such a value of the duration of hydromechanical processing at which a further increase in duration does not significantly increase the amount of moisture that can be absorbed by leguminous grains. It was this value of the duration of hydromechanical treatment that was considered rational.

The rational duration of hydromechanical processing was considered to be the one for which the kinetics of the moisture content of the studied types of raw materials was close to linear, where the end point is the value of the maximum moisture content of legumes.

At the same time, the Pearson correlation coefficient was found for the data to be approximated and the approximate linear function. Adding the values of the current moisture content to the subarray of data that was subject to approximation processing was carried out until the correlation coefficient reached the value of 0.9. Using the approximation function that satisfies the value of the correlation coefficient of 0.9 (straight lines of the corresponding color in Fig. 1), we searched for the point of its intersection with the kinetics of the moisture content obtained according to the proposed physical-mathematical model. The values of the duration of hydromechanical treatment corresponding to these intersection points were considered to be maximum (marked as τ_{r1}, τ_{r2}, τ_{r3}, τ_{r4} in Fig. 1). For the studied types of legumes, these values are respectively equal, min.: τ_{r1}=400, τ_{r2}=347, τ_{r3}=290, τ_{r4}=240.

Table 2 gives the ranges of duration values at which the maximum moisture content of leguminous grains is reached during hydromechanical processing.

Table 2

Ranges of duration values at which the maximum moisture content of leguminous grains is reached during hydromechanical processing

The name of legumes	Duration of water absorption, τ_r, min
Chickpeas	380...420
Bean	329...365
Pea	275...305
Lentil	228...252

Obviously, specifying the duration ranges that correspond to the achievement of the maximum moisture content of the legume grains is more convenient during their practical application. These duration ranges were chosen in such a way that the minimum and maximum duration values differ from the values obtained from Fig. 1 by no more than 5 %.

5. 2. Investigating the content of dry substances in aquafaba during hydromechanical processing

The stage of hydrothermal treatment is more significant in view of the formation of functional and technological properties of both boiled beans and aquafaba.

Accumulation of dry matter in aquafaba was investigated depending on the ratio of legume grain: water, temperature, duration of hydrothermal treatment and introduction of citric acid and sodium bicarbonate into the cooking medium.

At the first stage, the influence of the legume grain:water ratio on the content of dry matter in aquafaba was investigated. Fig. 2 shows the kinetics of dry matter content in aquafaba during the hydrothermal treatment of legume grains at a temperature of 99±1 °C. The ratio between raw materials and water in Fig. 2 was 1:1.5 for chickpeas, beans, peas, and 1:2.0 for lentils, and in Fig. 3 – 1:2.5 for chickpeas, beans, peas, and 1:3.0 for lentils.

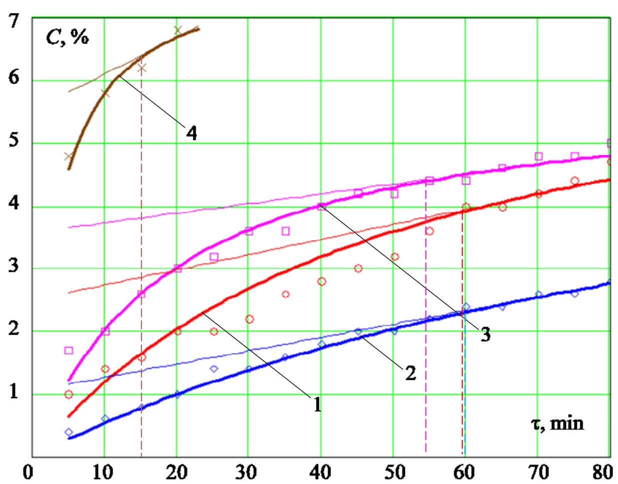

Fig. 2. Kinetics of the content of dry substances in aquafaba at a hydrothermal treatment temperature of 99±1 °C: 1 – chickpeas; 2 – beans; 3 – peas; 4 – lentils (ratio of raw materials: water – 1:1.5 for chickpeas, beans, peas, and 1:2.0 for lentils)

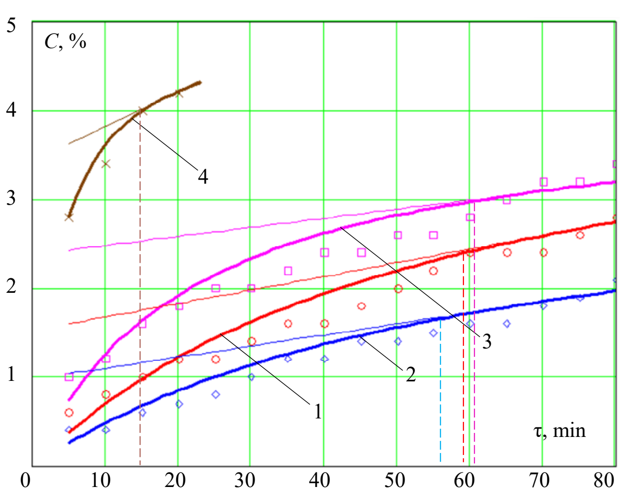

Fig. 3. Kinetics of the content of dry substances in aquafaba at a hydrothermal treatment temperature of 99±1 °C: 1 – chickpeas; 2 – beans; 3 – peas; 4 – lentils (ratio of raw materials: water – 1:2.5 for chickpeas, beans, peas, 1:3.0 for lentils)

Approximation of the experimental data was carried out using the physical-mathematical model by Peleg (5). The derived Peleg's constants for legumes for different ratios of legumes:water are given in Table 3.

Table 3

Peleg's constants and rational duration of hydrothermal treatment of leguminous grains at a temperature of 99±1 °C for different leguminous:water ratios

Name of legumes/ratio of legumes:water	Value of Peleg's constants		Ranges of rational duration of hydrothermal treatment, min.
	K_1	K_2	
Chickpea/1:1.5	7.000	0.138	54...66
Chickpea/1:2.5	12.000	0.214	54...66
Beans/1:1.5	17.000	0.150	54...66
Beans/1:2.5	17.750	0.286	49...61
Pea/1:1.5	3.235	0.168	50...62
Pea/1:2.5	5.500	0.244	54...66
Lentil/1:2.0	0.458	0.127	14...16
Lentil/1:3.0	0.786	0.198	14...16

The kinetics of the content of dry matter in aquafaba for leguminous grains at different ratios of leguminous grain:water have a similar character: the content of dry matter increases as the duration of processing increases, monotonically tending to the maximum value. Based on this pattern, it is obvious that there is a rational duration of hydrothermal treatment. The rational duration is understood as the processing time, when it is increased by at least 20 % of the total duration, the dry matter content increases by no more than 10 % of the total content.

Such values for the studied raw materials are, min.: chickpea (1:1.5) – 60; chickpeas (1:2.5) – 59; beans (1:1.5) – 60; beans (1:2.5) – 55; peas (1:1.5) – 56; peas (1:2.5) – 62; lentils (1:2.0) – 15; lentils (1:3.0) – 15. In Table 3, the rational duration of the studied raw materials is given in the form of ranges, where the minimum and maximum value of the duration differs by no more than 5 % from the values determined graphically.

At the next stage, the kinetics of the content of dry substances in aquafaba at temperatures of 99±1 °C and 120±1 °C were investigated. The results are shown in Fig. 4.

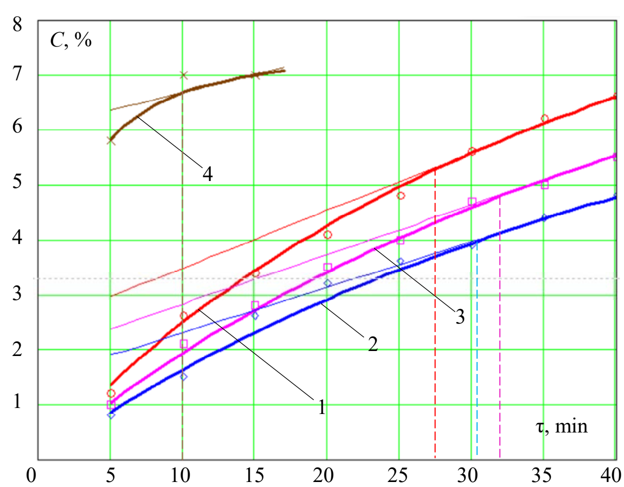

Fig. 4. Kinetics of dry matter content in aquafaba at a hydrothermal treatment temperature of 120±1 °C: 1 – chickpeas; 2 – beans; 3 – peas; 4 – lentils (legume: water ratio – 1:1.5 for chickpeas, beans, peas, and 1:2.0 for lentils)

The kinetics of dry matter content were approximated using the analytical form of Peleg's physical-mathematical model. Peleg's coefficients are given in Table 4.

Table 4

Peleg's constants and the rational duration of hydrothermal treatment of leguminous grains at a temperature of 120±1 °C for the ratio of leguminous grain:water – 1:1.5 for chickpeas, beans, peas, and 1:2.0 for lentils

The name of legumes	Value of Peleg's constants		Ranges of rational processing time, min.
	K_1	K_2	
Chickpeas	3.333	0.068	26...29
Bean	5.375	0.075	28...33
Pea	4.500	0.068	30...34
Lentil	0.215	0.129	9...11

Table 4 also gives the ranges of rational duration of hydrothermal treatment of the studied raw materials at a temperature of 120±1 °C. These ranges were determined similarly to the duration ranges given in Table 3.

5. 3. Investigating the effect of citric acid and sodium bicarbonate on the accumulation of dry substances in aquafaba during hydrothermal treatment

The results of investigating the influence of citric acid and sodium bicarbonate on the accumulation of dry substances in aquafaba from chickpeas, beans, peas, and lentils are shown in Fig. 5–8. The raw material:water ratio for the initial samples was 1:1.5 for chickpeas, beans, peas, and 1:2.0 for lentils, respectively. The temperature of the hydrothermal treatment was 99±1 °C.

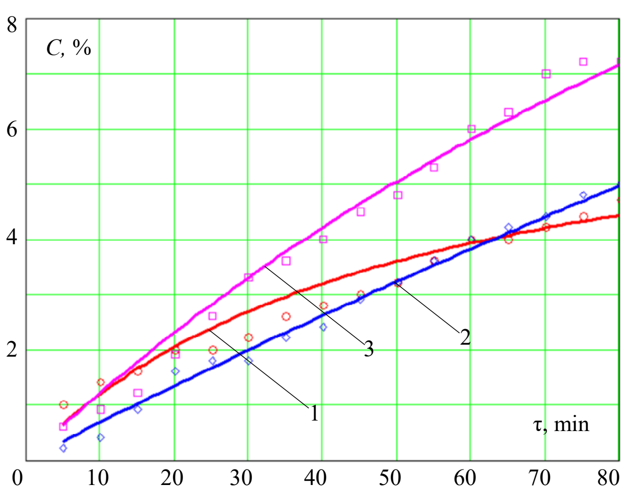

Fig. 5. Kinetics of the content of dry substances in aquafaba for different durations of hydrothermal processing of chickpeas in the cooking medium: 1 – drinking water; 2 – citric acid solution (pH 5.0±0.1); 3 – sodium bicarbonate solution (pH 8.0±0.1)

The dependences of changes in the amount of dry matter in aquafaba obtained as a result of hydrothermal treatment of leguminous grains in different environments are similar in nature. The amount of dry matter increases monotonically with increasing duration of hydrothermal treatment. Obviously, it should be expected that with an increase in the duration of hydrothermal treatment relative to the values considered in the experiment, the amount of dry substances in aquafaba will tend to its maximum value.

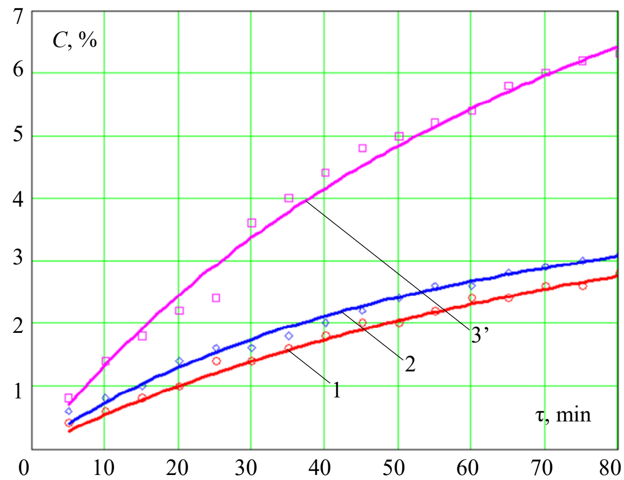

Fig. 6. Kinetics of dry matter content in aquafaba for different durations of hydrothermal processing of beans in the cooking environment: 1 – drinking water; 2 – citric acid solution (pH 5.0±0.1); 3 – sodium bicarbonate solution (pH 8.0±0.1)

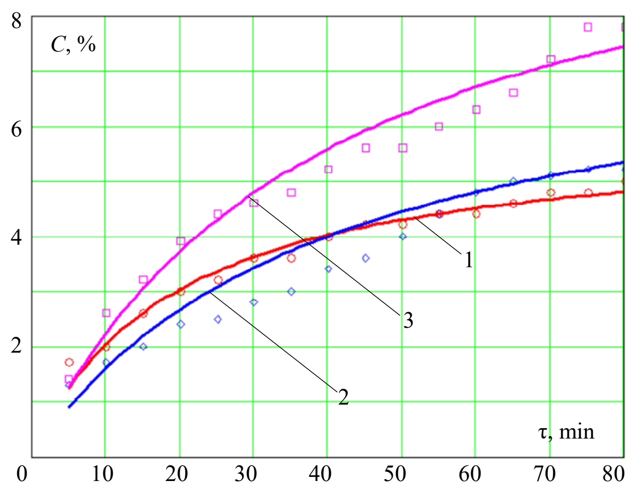

Fig. 7. Kinetics of the content of dry substances in aquafaba for different durations of hydrothermal treatment of peas in the cooking medium: 1 – drinking water; 2 – citric acid solution (pH 5.0±0.1); 3 – sodium bicarbonate solution (pH 8.0±0.1)

Table 5 gives the values of Peleg's constants for the kinetics of dry matter content in aquafaba obtained during the hydrothermal treatment of leguminous grains in the medium of drinking water, citric acid solution, and sodium bicarbonate for the studied types of leguminous plants.

Table 5

Peleg's constants for the kinetics of dry matter content in aquafaba after adding citric acid and sodium bicarbonate to the cooking medium

The name of legumes	Cooking medium			
	Citric acid solution (pH 5.0±0.1)		Sodium bicarbonate solution (pH 8.0±0.1)	
	K_1	K_2	K_1	K_2
Chickpeas	14.5	0.020	7.833	0.042
Bean	11.830	0.177	6.75	0.071
Pea	5.0	0.125	3.571	0.090
Lentil	0.919	0.094	0.328	0.100

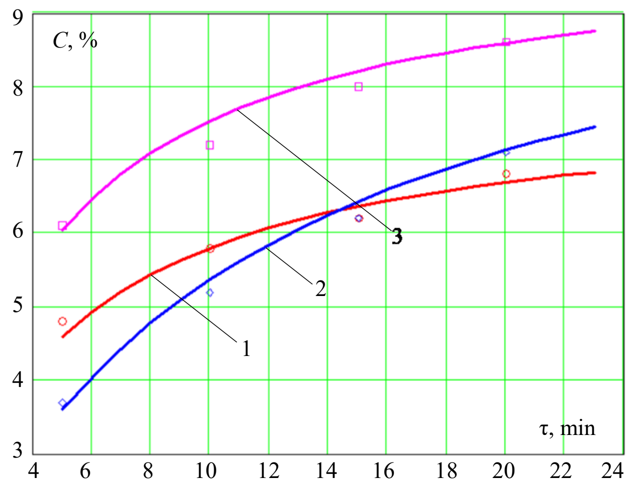

Fig. 8. Kinetics of dry matter content in aquafaba for different durations of hydrothermal treatment of lentils in the cooking medium: 1 – drinking water; 2 – citric acid solution (pH 5.0±0.1); 3 – sodium bicarbonate solution (pH 8.0±0.1)

It should be noted that K_1 is Peleg's constant, the dimensionality of which in %/min corresponds to the rate of transition of dry substances into solution during hydrothermal treatment of raw materials. K_2 is the Peleg capacity constant, which is inversely proportional to the maximum level of dry substances that diffuse into the solution. Based on this, the constants given in the table make it possible to formulate recommendations regarding the environment in which hydrothermal treatment should be carried out in accordance with production requirements.

The margin of error in studies was σ=3...5 %, the number of repeated experiments was n=3, the probability was $p \geq 0.95$.

6. Discussion of results related to the influence of hydrothermal treatment of leguminous grains on the accumulation of dry substances in aquafaba

The kinetics of moisture content are determined by the properties of leguminous grains. In particular, the chemical composition and physical state of dry substances, the diffusion properties of their shell, etc., as well as the liquid in which the grain is located, namely its chemical composition and physical properties. Establishing the analytical dependence of the rate of change in moisture content due to the absorption of the wetting liquid by the studied samples is a difficult task, especially given the fact that raw materials such as leguminous grains are native plant raw materials. Based on this, a simplification was adopted in the study, which implies using the experimental value of the rate of change of moisture content in the moisture content kinetics model (4).

Obviously, the proposed physical-mathematical model is partially empirical from the point of view of the theory of the process of moisture content kinetics. However, from the point of view of convenience, its use during the processing of leguminous grains to obtain cooked legumes and aquafaba is acceptable.

Investigating the hydration behavior of leguminous grains is necessary for the predicted course of the technological process for obtaining a finished product with specified properties. The difference in the kinetics of water absorption by legume grains is related to the biological characteristics of different types of legume, which is reflected in different physical parameters. The specified parameters include the thickness of the seed wall, the size and area of the seed, the initial humidity, and the integrity of the legume. Thus, according to our data, legumes with a larger surface area are characterized by a longer duration of hydration of dry grains, which is confirmed by the example of chickpeas. In chopped or small-sized legume grains, the water absorption process occurs faster, which is reflected in the results of water absorption kinetics for peas and lentils (Fig. 1).

Papers [21, 22] previously reported a change in the moisture content of leguminous grains during soaking. This made it possible to expand the validity of scientific conclusions regarding certain varieties of legumes but grown in different climatic zones. These results cannot be reliably applied to other types of legumes.

Equilibrium grain moisture is achieved when water diffuses through semipermeable cell membranes and the seed coat into the center of the seed, filling all intercellular spaces. The specified process is accompanied by swelling of cell walls, starch grains, protein matrix, weight increase compared to the initial one. The water absorption of legume grains has a predictable behavior, rapid water absorption at the beginning and a slowing of the process until the full liquid absorption equilibrium is reached.

An increase in the duration of hydromechanical processing of the studied leguminous grains relative to the ranges of values given in Table 2 does not lead to a significant increase in the moisture content of this raw material. That is, the increase in moisture content occurs by no more than 10 %, provided that the duration of hydromechanical processing is increased by 2...2.5 times, which is impractical.

Thus, the calculated ranges of maximum water absorption values of leguminous grains during hydromechanical processing (Table 1) were chosen as rational for practical use in the technological process for preparing chickpeas, beans, and peas. However, the biological features of lentils, in particular, the thickness of the grain shell, the dimensional characteristics of the grains, contribute to a much faster hydration process compared to other types of legumes. Because of this, prolonged hydromechanical processing, which exceeds 2 hours, leads to excessive softening, but this step is necessary to reduce the content of anti-nutrients.

Unlike [5, 6], in which the influence of acidic and alkaline environments on the properties of leguminous grains was studied, the results of our study reflect the influence of temperature, hydro modulus, and pH mainly on the accumulation of dry substances in aquafaba.

Using the main method of bringing rehydrated leguminous grains to readiness makes it possible to optimize the technological process by varying such parameters as the hydro module and the duration of cooking. This approach makes it possible to obtain aquafaba with a rational content of dry substances and a yield of 70–75 % of the initial content of the used water.

Cooking under pressure of 120±1 °C made it possible to reduce the total duration of bringing the beans to readiness by two times (Table 4), while simultaneously increasing the content of dry substances in aquafaba. However, the use of this method leads to obtaining aquafaba in the amount of 30–35 % of the initial water content for chickpeas and beans, 20–25 % for peas and lentils.

A hydro module of 1:1.5 was chosen for chickpeas, beans, peas, and 1:2 for lentils in order to achieve higher values of dry matter content in aquafaba, which at the same time provides conditions for bringing the legume grains to culinary readiness. In addition, the accumulation of dry matter in aquafaba depends on the duration of hydrothermal treatment (Table 3), respectively 60–80 min for chickpeas, beans, peas, and 5 min for lentils. This makes it possible to obtain boiled legumes with high organoleptic indicators and aquafaba with a dry matter content of 2.8–4.8 % (Fig. 2, 3). Prolonged duration of hydrothermal treatment leads to damage and rupture of the seed coat of leguminous grains and the transfer of dry substances into the cooking medium. In [13], research is highlighted in which the content of dry substances in aquafaba is 11.3–15.0 %. This becomes possible owing to the variation of chickpea processing parameters – hydro module, cooking duration, and temperature.

During the hydrothermal processing of legume grains in a cooking medium with a pH of 5.0±0.1, acid hydrolysis of starch occurs, which causes physicochemical changes. The destruction of the integrity of starch grains and depolymerization of starch polysaccharides with the formation of substances with a lower molecular weight (dextrin) takes place. The specified process can explain the slightly higher content of dry matter in aquafaba obtained under the specified parameters (Fig. 5–8). However, simultaneously with the described changes in aquafaba, the hydrothermal treatment of legume grains in a cooking environment with a pH of 5.0±0.1 led to a slowdown in the process of softening of the seed coat. This caused a delay in the transition of protopectin into pectin, which increased the duration of bringing the beans to culinary readiness.

Hydrothermal treatment of leguminous grains in a cooking environment with a pH of 8.0±0.1 reduced the duration of hydrothermal treatment due to the breaking of intermolecular bonds, which intensified the swelling of starch grains, accelerated the destruction of protopectin from the accumulation of soluble pectin. Alkaline environment also affects the solubility of existing proteins, increasing their extraction due to the breakdown of the protein matrix. The specified physicochemical changes led to significantly higher values of dry matter content in aquafaba compared to samples without the addition of sodium bicarbonate (Fig. 5–8), but this negatively affected the organoleptic indicators of both boiled legume grains and aquafaba. This was manifested in a change in the color of beans and aquafaba and the presence of a residual alkaline aftertaste.

Our studies revealed the effect of hydrothermal processing of legume grains on the accumulation of dry substances in aquafaba depending on the temperature, duration of cooking, hydro modulus, and pH of the medium. This has made it possible to determine the rational parameters for the technological process of obtaining boiled beans and aquafaba with a given content of dry substances, taking into account the Peleg constants, which are indicated in Tables 3–5.

The practical implementation of our research results was carried out within the framework of the development of technology for snacks with an emulsion structure based on boiled leguminous grains and aquafaba.

Compared to studies [14, 15], in which attention is mostly concentrated on one type of legume (mainly chickpeas), the research subjects have been significantly expanded, which is important in view of the scientific and practical significance of the results.

However, the limitation of the results is that the experimental studies were carried out for specific varieties of the selected legumes. Temperature, as a factor affecting the rate of kinetics of moisture content, was not taken into account because investigating the rate of kinetics was carried out at a temperature of 18±0.5 *°C*, accordingly, approximation by the Arrhenius equation was not carried out. The loss of dry matter during hydromechanical processing is not taken into account since the absorption of liquid by the legume grains exceeds the loss of dry matter. In addition, the liquid after hydromechanical treatment is not reused due to the presence of anti-nutrients. In the review of the literature, no studies on a direct correlation between the chemical composition and the hydration kinetics of legumes were found, but conditionally this factor is taken into account because it affects the physical parameters and structure of legume grains, the porosity of the shell, and the chemical composition.

The lack of research on the quantitative and qualitative composition of aquafaba in relation to the content of dry substances, which affects the realization of the technological properties of aquafaba, in particular, the ability to foam, emulsify, gel, etc., is identified as a drawback of the work.

Biological diversity, varietal characteristics of legumes affect the technological process of obtaining aquafaba and its functional and technological properties. This complicates the process of its research and leads to high variability of experimental data. For these reasons, the prospect of further research is to determine the chemical composition of aquafaba obtained with the parameters of the technological process specified in this paper.

7. Conclusions

1. A physical-mathematical model was applied to the array of data on the kinetics of the moisture content of the studied legume grains, an approximation of the experimental values was carried out, which made it possible to formulate rational parameters of hydromechanical processing. During hydromechanical treatment, intensive absorption of moisture occurs in the first hours and reaches up to 80 % of the initial mass. After that, the intensity of water absorption decreases slightly, but continues to increase by 1–3 % in half an hour until equilibrium is reached. The rational duration of hydromechanical processing of leguminous grains is the duration (hours) at which 90 % swelling of leguminous grains from the initial mass is achieved: chickpeas – 7.0–8.0, beans – 4.5–5.0, peas – 4.0–4.5, lentils – 1.5–2.0.

2. Rational technological parameters have been established in the relationship "achieving the readiness of leguminous grains – the content of dry substances in aquafaba". The latter is determined by the kinetics of accumulation of dry substances in aquafaba and will affect its technological purpose. Two standardized technologies of hydrothermal treatment of leguminous grains were selected. The first technology (main method) involves cooking leguminous grains at a hydro module of 1:1.5 for chickpeas, beans, peas, 1:2.0 for lentils, for 60–80 min for chickpeas and beans, 40–60 min for peas, 5–7 min for lentils at a temperature of 99±1 °C. The second is pressure cooking of leguminous grains using a pressure cooker at a hydro module of 1:1.5 for chickpeas, beans, peas, 1:2 for lentils for 5–40 min at a temperature of 120±1 °C. Under these parameters, the content of dry matter in aquafaba is 2.8–4.8 % for cooking in the main method and 3.9–7.0 % for using a pressure cooker.

Approximation of the obtained results was carried out using the Peleg model.

3. The addition of citric acid or sodium bicarbonate to the aqueous solution for the hydrothermal treatment of leguminous grains (the main technique) increased the kinetics of accumulation of dry substances in aquafaba. With the introduction of citric acid, the content of dry substances in aquafaba was 3.1–7.1 %, sodium bicarbonate – 6.3–8.6 %. However, taking into account the negative impact of additives on the organoleptic indicators of boiled beans and aquafaba, it is not advisable to use them in the technology of food products.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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