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Ground Ivy (*Glechoma hederacea* L.) as an Innovative Additive for Enriching Wheat Bread: Study on Flour Fermentation Properties, Dough Rheological Properties and Bread Quality

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Abstract: The aim of the study was to assess the effect of water infusion of dried and crushed ground ivy (GH) on the fermentation properties of wheat flour (WF), farinographic properties of flour and dough (WD) and the quality of the obtained bread. In the tested systems, tap water was replaced with water infusion with GH (m/v) at a concentration of 1% (A), 3% (B) and 5% (C). As part of the research methodology, the fermentation properties of flour and rheological properties of dough were assessed using a farinograph, and bread was obtained using a single-phase method using yeast and its quality was assessed. As part of this, the antioxidant potential and the profile and level of polyphenol content were determined. It was shown that replacing water with GH infusions shortened the total fermentation time of the dough and reduced the fermentation capacity of the dough. In the farinographic evaluation, an increase in flour water absorption (54.0–57.0%), dough development time (2.3–7.6 min), dough stability and softening were observed with an increase in the concentration of the added GH infusion. In turn, the volume of the loaf and the specific volume of the bread decreased with increasing the concentration of the GH infusion. The bread crumb darkened, and the elasticity and chewiness of the crumb decreased in relation to the control sample. In turn, the presence of GH infusion did not significantly affect the hardness of the crumb. As the concentration of the added GH infusion increased, an increase in the antioxidant potential of bread and the content of polyphenols and flavonoids was observed, and the UPLC-PDA-MS/MS analysis allowed the identification of 11 polyphenols in the bread.

Keywords: bread; food fortification; herbal infusion; polyphenols



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1. Introduction

Bread is one of the main cereal grain products consumed by consumers worldwide [1,2]. In the case of wheat bread, its main ingredient is flour made from milling wheat grain. The widespread consumption of wheat bread or other types of bread results from the dominance of wheat (*Triticum aestivum* L.) in the structure of cereal crops worldwide. As a result, wheat grain, or rather products based on it, is a component of the daily diet of about 4.5 billion people living in nearly 95 countries around the world [3]. The chemical composition of bread includes carbohydrates, mainly starch, protein, a small amount of fat, as well as minerals and vitamins [4,5]. However, bread made from refined flour, largely devoid of bran particles, is poor in minerals, vitamins, dietary fiber and valuable phytochemicals with biological potential. Therefore, in the case of this type of bread, there is a need to improve its chemical composition by enriching it with plant raw materials. For years, researchers have been successfully conducting scientific research on the possibilities of using, among others, plant-based raw materials, including food industry by-products, for the process of enriching bread. Numerous examples include enriching bread using chia seeds [6–8], amaranth [9], pumpkin [10], leaves [11,12], flowers [4,13] and seeds of other

pseudocereals [14] or legumes [15]. The trend related to the use of by-products such as pomace, cake, spent grain, bran, etc. [16–18], for enriching bread is particularly important. Such practices are consistent with the circular economy strategy and the economic and ecological policy of the European Union [19].

Ground ivy (*Glechoma hederacea* L.) is a wild plant with medicinal and spice significance [20]. Botanically, this plant belongs to the *Lamiaceae* Lindl family. It usually grows in moist, shaded and heavy soils. However, it also tolerates open and sunny areas well. Ground ivy has climbing stems with serrated, dark green heart-shaped leaves. The flowers are purple-blue and tubular in shape. The plant blooms from March to June [21,22]. As a spice plant, it was initially used to season beer, as a substitute for hops or as a substitute for parsley leaves used for cooking soups and other dishes [20]. In turn, from the pharmacological point of view, researchers have found beneficial properties of the ground ivy herb as a mild medicinal agent with expectorant, catarrh-curing, astringent, anti-inflammatory, diuretic, stomachic effect or as an agent in dermatological treatments [22,23]. The therapeutic properties of ground ivy infusions are related to the bioactive substances that occur in this plant. The chemical composition of *Glechoma hederacea* L. includes alkaloids (Hederacine A, Hederacine B), volatile oils, diterpenes, triterpenes, phenolic acids (caffeic acid, ferulic acid, sinapic acid), phenolic glycosides, flavonoids and many other substances with health-promoting potential [22,23].

The presented research is pioneering and innovative, as it serves to assess the potential application possibilities of the ground ivy herb in the bakery industry. Therefore, the aim of the work was to assess the effect of ground ivy infusion of different concentrations on the fermentation and rheological properties of wheat flour and dough, as well as to assess the quality of the obtained bread.

2. Materials and Methods

2.1. Material

Wheat flour was subjected to analysis of its basic chemical composition, gluten content and quality, and an evaluation of fermentation properties and water absorption using a farinograph. Dough was subjected to farinograph analysis. Bread was obtained using a single-phase dough method using yeast and its quality was assessed, including laboratory baking parameters, crumb and crust color, crumb texture, antioxidant properties and total polyphenol and flavonoid content. Polyphenols contained in bread were also identified using the UPLC-PDA-MS/MS method.

Type 650 wheat flour (Podlaskie Zakłady Zbożowe, Białystok, Poland), fresh baker's yeast (*Saccharomyces cerevisiae*) (Lallemand Sp. z o.o., Józefów, Poland), iodized salt (o'Sole, Września, Poland) and dried ground ivy (*Glechoma hederacea* L.) were used in the study. Ground ivy was collected in April 2024 in the Subcarpathia region. After collection, the plant material was frozen and then dried by the freeze-drying method using a freeze dryer (ALPHA 1–2 LD plus Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany). The dried plants were ground into powder using a laboratory mill. For the tests, water infusions of the ground ivy herb (GH) were used with a percentage (%) mass per volume (m/v): 1, 3 and 5, which replaced the water calculated in the bread recipe (A, B, C). Therefore, 1, 3 or 5 g of GH d.w. (dry weight) was poured with 100 mL of hot water (85 °C) and brewed for 10 min under cover. After this time, the whole was filtered, and the clear infusion was cooled to 25 °C and used for the tests.

2.2. Methods

2.2.1. Chemical Analysis of Flour

The proximate analysis of the flours was carried out to determine: moisture content (%) according to the Polish Standard PN-EN ISO 712:2012 [24], quantity of wet gluten according to the Polish Standard PN-EN ISO 21415-1:2007 [25] and Jakubczyk and Haber [26] description, Zeleny sedimentation indicator using measuring set (Sadkiewicz Instruments, Bydgoszcz, Poland) described by Polish Standard PN-EN ISO 5529:2010 [27], falling num-

ber using Falling Number 1900 measuring apparatus (Perten Instruments, Huddinge, Sweden) according to Standard ICC No. 107/1 [28], fat acidity according to the PN-ISO 7305:2001 [29], protein and ash content (% of dry weight, d.w.) using a DA 7200 NIR analyzer (Perten Instruments, Huddinge, Sweden) equipped with a stationary monochromator and a diode array detector.

2.2.2. Fermentation Properties of Flour

The fermentation properties of the flour and doughs were estimated using a BZS SZ 2005-type laser fermentograph (Sadkiewicz Instruments, Bydgoszcz, Poland). Selected doughs (corresponding to the single-phase baking method) were prepared from 140 g flour, 2.5 g baker's yeast, 2 g salt and 80 mL water infusions of *Glechoma hederacea* L. using a JŻ 750 type laboratory kneader (Sadkiewicz Instruments, Bydgoszcz, Poland) and placed in the fermentograph chamber, at 35 °C [30].

A single analysis was performed for 90 min and every 2 min dough volume was measured. Based on the fermentographic analysis the following parameters were determined: optimal time of dough fermentation (min), total volume of CO₂ produced in fermentation time (cm³), volume of CO₂ retained in the dough in fermentation time (cm³) and volume of CO₂ released outside the dough in fermentation time [30].

2.2.3. Farinographic Analysis of Flour and Dough

Farinographic analysis was performed using a Brabender farinograph-E (Brabender GmbH & Co. KG, Duisburg, Germany) in accordance with ICC Standard No. 115/1 [31]. A flour mass equivalent in terms of dry matter content to 50 g of flour with a moisture content of 14% was used in the tests. In the tests of doughs enriched with the infusion, instead of water used in the control test (control), a water infusion of *Glechoma hederacea* L. (1, 3 and 5%) was used (A, B, C). The analysis determined the water absorption of the flour (%), dough development time (min), dough stability (min), dough softening degree (FU) and the farinographic quality number (FQN). The results were collected using Farinograph software (Version 4.0.2, IDENT No. 72000) for operating the farinograph. The analysis of each test system was performed in triplicate.

2.2.4. Laboratory Baking of Bread

The bread was made using the direct method using baker's yeast [12,13,26]. Briefly, the dough recipe included wheat flour, yeast in the amount of 3% of the flour mass, salt (1.5% of the flour mass) and water or GH infusions, in the amount calculated based on the water absorption of the flour, to a dough consistency of 350 FU [26]. The temperature of the water or GH infusion was 35 °C. The weighed dough ingredients were thoroughly mixed in an R4 mixer (Mesko-AGD, Skarżysko-Kamienna, Poland). The total fermentation time in the fermentation chamber (36 °C) was 60 min, and after 30 min the dough was mixed for 1 min. After the fermentation was completed, 250 g dough pieces were formed, then placed in greased molds and placed in the fermentation chamber for optimal rising. Baking was carried out at 230 °C in a Classic electric oven (Sveba Dahlen, Fristad, Sweden) for 30 min. After baking, the hot breads were weighed and then left to cool at room temperature. Further analyses of the bread were performed 24 h after baking.

2.2.5. Baking Process Parameters

As part of the evaluation of the baking process parameters of the tested breads, dough yield (%), oven loss (%) and bread yield (%) were determined [26].

2.2.6. Bread Quality Assessment

The volume of bread loaves [cm³] was determined using the laboratory method using millet grain AACC Method No. 10-05.01 [32] and the specific volume of bread [cm³/g], taking into account the mass of the cooled bread. The porosity and moisture of the bread

crumb were determined [26]. Bread crumb porosity was determined using the Dallman scale [26]. Analyses were performed in triplicate.

Measurements of the color parameters of the crust and bread crumb were performed using the CIE L*a*b* model using the UltraScan Vis spectrophotometer (HunterLab, Reston, VA, USA) [12,13]. As part of this analysis, the L* parameter defining the lightness, a* (red/green color saturation) and b* (yellow/blue color saturation) were measured. In addition, the total color difference (ΔE) between the control bread and the breads enriched with GH infusion was calculated. The ΔE parameter was calculated according to the mathematical relationship:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$$

The determinations and calculations were performed in triplicate.

After 24 h from baking, samples of bread crumbs were cut out in the shape of a cuboid with dimensions of $30 \times 30 \times 40$ mm. Texture analysis using the TPA test was performed using an EZ-LX texturometer (Shimadzu, Kyoto, Japan) with Trapezium X Texture PL software (Shimadzu, Kyoto, Japan). The crumb sample was subjected to double compression with a head movement speed of $v = 50$ mm/s to 50% of the sample height. The measurement was made using a 25 mm diameter disk-shaped probe. As part of the analysis, hardness (N), cohesiveness (-), springiness (-) and chewiness (N) were determined. The tests were performed in 5 repetitions.

2.2.7. Total Phenolics and Flavonoids Content and Antioxidant Potential of Wheat Bread with Addition of *G. hederacea* Infusion

Samples of control and fortified bread were frozen, freeze-dried and ground. The extracts were prepared following the method described by Pycia et al. [12].

The total content of phenolic compounds (TPC) was assessed according to Gao et al. [33]. The results were expressed in mg of gallic acid per 100 g of dry weight (mg GAE/100 g d.w.). The total content of flavonoids (TFC) was assessed in accordance with Chang et al. [34]. The results were expressed as mg of quercetin (mg QE/100 g d.w.). The tests were executed in triplicate.

ABTS⁺ radical scavenging activity assay (ABTS) was assessed according to Re et al. [35]. Ferric Reducing Antioxidant Power (FRAP) test was performed according to Benzie and Strain [36]. The findings were expressed as mM of Trolox (mM TE/100 g d.w.). The tests were performed in triplicate.

2.2.8. Chromatographic Analysis of Wheat Bread with Addition of *G. hederacea* Infusion

Extracts for the chromatographic analysis were prepared according to the protocol reported above [12] and then purified following the procedure introduced in the study of Kaszuba et al. [37].

Determination of phenolic profile was executed by means of UPLC-Q-TOF-MS (Waters, Milford, MA, USA) in accordance with the methodology described by Pawłowska et al. [38]. Analyses were performed using a UPLC BEH C18 column (100 mm $\times$ 2.1 mm, 1.7 μ m, Waters, Warsaw, Poland) of water (solvent A) and 40% acetonitrile in water, v/v (solvent B). The solvent gradient was as follows: 0–8 min, 5–100% B, 8–9.5 min washing, and coming back to initial conditions. Elution was performed at a flow rate of 0.35 mL/min. The volume of injection was 5 μ L. The conditions for triple-quadrupole detection were optimized, and the parameters were as follows: gas flow con 100 L/h; voltage 30 V; capillary voltage 3.5 kV; source temperature 120 °C; desolvation temperature 350 °C; and desolvation gas flow 800 L/h. The quantification of polyphenolic compounds was performed by the use of the internal standard method. Chlorogenic acid, quercetin 3-O-rutinoside, vitexin and kaempferol 3-O-glucoside were selected as internal standards of calibration for phenolic acids, quercetin, apigenin and kaempferol derivatives, respectively. Results are expressed in μ g/1 g d.w.

2.3. Statistical Analysis of Research Results

Mean values of the parameters and standard deviations were calculated using Excel 2016 (Microsoft Corp., Redmond, WA, USA). The results were subjected to one-way ANOVA. The significance of differences between means was tested using Duncan's test, at a significance level of $p = 0.05$. Statistical analysis was performed using Statistica 13.3 (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results and Discussion

3.1. Chemical Composition of Wheat Flour

Table 1 shows the values of parameters related to the chemical composition of wheat flour and its baking value.

Table 1. Proximate composition of the flour used for bread baking.

Flour Quality Parameters	Wheat Flour (Type 650)
Moisture content [%]	14.40 ± 0.03
Falling number [s]	438 ± 10
Wet gluten content [%]	34.87 ± 0.14
Zeleny sedimentation indicator [cm^3]	33 ± 2
Protein content [% d.w.]	13.67 ± 0.12
Fat acidity [mg KOH/100 g d.w.]	116.21 ± 9.55
Ash content [% d.w.]	0.74 ± 0.01

Mean values from three repetitions $\pm$ SD.

The study found that the wheat flour used for baking bread was of good quality. All the tested parameters of its baking value were in line with the quality standard [39]. Only the average values for the falling number (above 400 s) and fatty acidity were high, which may indicate a long storage period of the flour after milling the grain [26]. In terms of the amount of wet gluten, the flour used in the study was of good quality [39], because the amount of wet gluten was on average 34.87%, which is in line with the standard specifying the minimum level of washed wet gluten at 25%. The sedimentation index value was determined at 33 cm^3 , which is higher than the minimum value of 25 cm^3 . In the light of the studies of other authors [40], the tested wheat flour was assessed as a good quality product, suitable for bread production. The low amylolytic activity noted may indicate the need to extend the final fermentation time, which was determined by fermentographic analysis.

3.2. Fermentation Properties of Wheat Flour

The use of a laser fermentograph allowed the effect of replacing water with a GH infusion of different concentrations on the ability to accumulate CO_2 produced by yeast during the optimal time of dough fermentation in a piece of the tested wheat dough to be assessed. In addition, the potential volume of a single loaf of bread was determined (the volume of CO_2 retained in the dough during fermentation).

Figure 1 and Table 2 present the results of fermentographic analysis of wheat flour doughs with the addition of ground ivy infusions at concentrations of 1, 3 and 5%.

The course of the fermentographic curves (Figure 1) reflects the volume of carbon dioxide produced, retained and lost during dough fermentation. Statistically significant differences were found between the samples for both the optimal dough fermentation time and the amount of released carbon dioxide ($p < 0.05$) (Table 2).

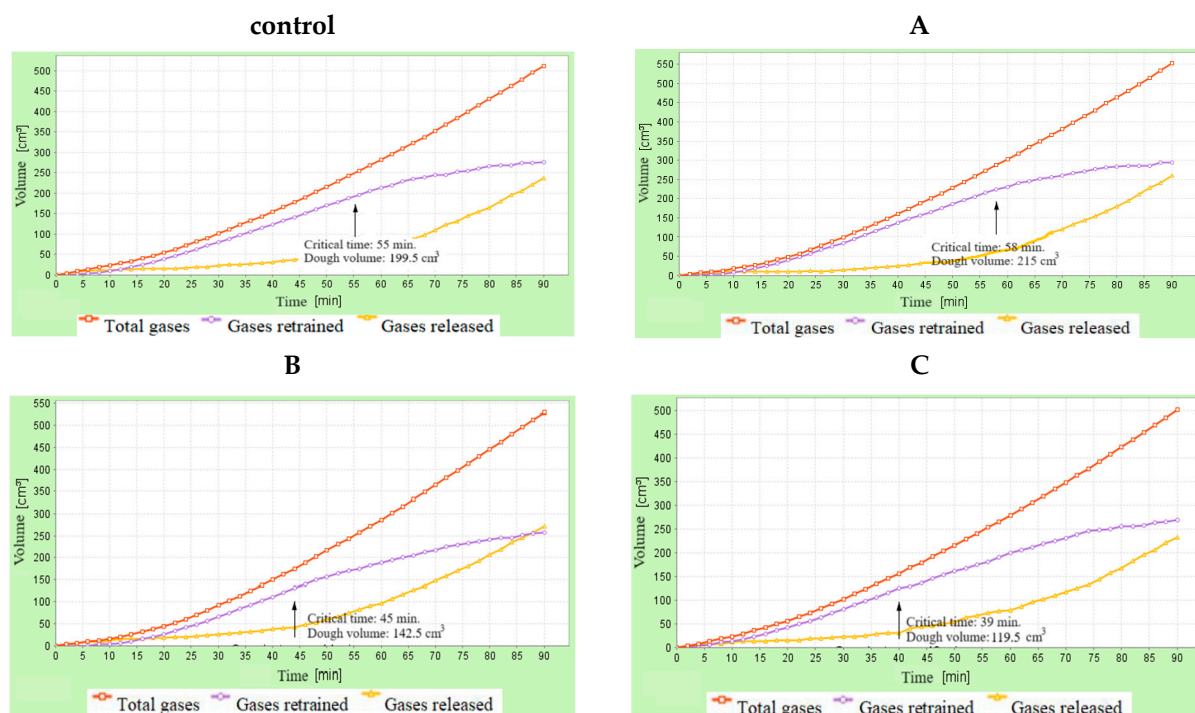


Figure 1. Fermentographic graphs of tested doughs: **control**—control sample with water; **A**—dough with 1% infusion; **B**—dough with 3% infusion; **C**—dough with 5% infusion.

Table 2. Fermentographic parameters of the tested flour and doughs with *G. hederacea* L. infusions.

Sample	Optimal Time of Dough Fermentation [min]	Total Volume of CO ₂ Produced in Fermentation Time [cm ³]	Volume of CO ₂ Released Outside the Dough in Fermentation Time [cm ³]	Volume of CO ₂ Retained in the Dough in Fermentation Time [cm ³]
control	55.0 ^c ± 1.4	254.5 ^c ± 3.5	55.0 ^c ± 1.4	199.5 ^b ± 4.9
A	58.0 ^c ± 0.0	277.5 ^c ± 13.4	62.5 ^d ± 0.7	215.0 ^b ± 12.7
B	45.0 ^b ± 1.4	185.5 ^b ± 16.3	43.0 ^b ± 1.4	142.5 ^a ± 14.8
C	39.0 ^a ± 1.4	150.5 ^a ± 7.8	31.0 ^a ± 0.0	119.5 ^a ± 7.8

Mean values from two repetitions ± SD. Values in columns followed by the same superscript letters do not significantly differ at a significance level of 0.05.

The use of infusions with a concentration of 3 or 5%, respectively, for the preparation of dough resulted in a reduction in the optimal dough fermentation time by 10 and 15 min compared to the time determined for the control sample (55.0 min). For these samples, the fermentation capacity of the flour (total volume of CO₂ released during dough fermentation) was also lower in the recorded fermentation time. In the case of the sample with 3% infusion, the volume was 65 cm³ smaller, and for the sample with 5% infusion, the total volume of CO₂ released was 100 cm³ smaller compared to the control sample, for which the value of this parameter was 254.5 cm³. This proves the significant, unfavorable effect of increasing the concentration of bioactive substances contained in the *G. hederacea* L. infusions used to prepare the dough on the activity of yeast during dough fermentation. Santetti et al. [41] showed that the addition of yerba mate leaves affects CO₂ production during dough fermentation. The amount of gas released during the fermentation process in the samples decreased ($p < 0.05$) with the increase in the share of yerba mate leaves addition. Based on the studies of the cited authors and the results of studies by other authors [42], it can be assumed that the presence of phytochemicals from *G. hederacea* L. infusions in the tested wheat dough could have led to the formation of complexes with the yeast structure and, consequently, to a decrease in yeast activity, which was manifested

by a change in fermentation parameters (Figure 1, Table 2). The above observations were also confirmed by the amount of CO₂ accumulated inside the dough samples (Table 2). Statistically significant differences ($p < 0.05$) were noted only between the control sample and the samples tested with 3 or 5% of the infusion, where the expected volume of the dough piece after fermentation was, respectively, 60 and 80 cm³ smaller than the control piece (199.5 cm³). Within this parameter, no significant differences were observed between the control sample and the sample with 1% infusion or between the samples with 3 and 5% infusion. In the case of the volume of gases released outside the dough, significant differences were noted between all the variants tested. The highest value of this parameter was characteristic of the sample with 1% of the infusion (62.5 cm³), while the lowest was characteristic of sample C (31.0 cm³). In comparison with the literature data, the fermentation time noted for the control sample (55.0 min) was similar. Sobczyk et al. [43] obtained an average fermentation time of 46–84 min for the tested doughs made of flour from different spelt varieties. The cited authors used dough made of flour from wheat variety Tonacja as a control sample, the fermentation time of which was 58.0 min. This time was also slightly longer (by 3 min) than that obtained in the discussed studies for the control sample (Table 2). Similar relationships were observed when comparing with the results presented by Belcar et al. [44], where the fermentation time of the control sample was 60 min. The volume of gases released by the control sample (Table 2) was also smaller in comparison with those reported by Sobczyk et al. [43] and Belcar et al. [44]. The cited authors obtained results for their own control samples that were 10 or even 100 cm³ higher than for the tested control sample (Table 2). The observed differences could be the result of using different types of wheat flour in the cited authors and our own studies (Table 1). Nevertheless, the fermentation properties of the dough are largely related to the presence of bioactive substances present in the GH infusion, which affects the activity of yeast. These substances probably have antimicrobial properties; i.e., they have an adverse effect on the activity of yeast. In numerous studies by other authors, the antimicrobial activity of *G. hederacea* L. herb extracts was confirmed, and their effectiveness and scope of action depended on the extraction method [45–47].

3.3. Water Absorption Capacity of Flour and Rheological Properties of Wheat Dough

Table 3 presents the results of the analysis of the water absorption capacity of wheat flour and the ability of the tested flour to absorb water infusions based on the ground ivy herb, as well as the results of the tests of the rheological parameters of the dough determined using a farinograph and obtained on the basis of the tested flour–water and flour–GH infusion systems (1, 3, 5%).

Table 3. Farinographic quality parameters of tested wheat doughs with *G. hederacea* L. infusions.

Sample	Water Absorption of Flour [%]	Dough Properties			
		Development Time [min]	Stability [min]	Softening [FU]	FQN
control	54.0 ^a ± 0.0	2.3 ^a ± 0.1	9.1 ^a ± 0.5	45 ^a ± 3	95 ^a ± 4
A	55.5 ^{a,b} ± 0.1	2.5 ^a ± 0.4	11.1 ^a ± 1.4	39 ^a ± 6	121 ^b ± 15
B	56.7 ^b ± 0.2	7.0 ^b ± 0.4	10.7 ^a ± 1.1	81 ^b ± 2	115 ^b ± 5
C	57.0 ^c ± 0.2	7.6 ^b ± 0.9	11.3 ^b ± 0.9	104 ^c ± 4	124 ^b ± 8

Mean values from three repetitions ± SD. Values in columns followed by the same superscript letters do not significantly differ at a significance level of 0.05.

Water absorption of the tested wheat flour was at the level of 54.4%, while its absorption in the case of using a 1% infusion of *G. hederacea* L. did not change. At the same time, it was noted that in the case of replacing water with infusions of higher concentration (3 and 5%), the absorption of flour increased statistically significantly ($p < 0.05$) with the increase in the concentration of the infusion.

Interesting observations were made when comparing the results of the dough development time (DDT) measurement as the control sample and the sample with 1% infusion of ground ivy herb (A) did not differ statistically significantly in terms of this parameter, and the average DDT was 2.4 min. However, in the case of the next two experimental systems (B, C), an extension of the dough development time was noted, even 3-fold (C). Moreover, it was found that different concentrations of the *G. hederacea* L. infusions used differentiated the discussed parameter between samples B and C. The next parameter tested was dough stability, which remained at the same level in the tested control sample systems and A and B. Therefore, neither replacing water with infusion nor its different concentrations (1 and 3%) had no statistically significant effect on the dough stability time. When using 5% infusion, an improvement in dough stability was noted. The softening of the control dough and dough A was similar, but the use of *G. hederacea* L. infusions at a higher concentration caused a significant increase in dough softening, and in the case when 5% GH infusion was used instead of water, it was over 55% higher. The farinographic quality number was higher for the tested systems in which water in the dough was replaced with GH herb infusion. The use of 1% infusion did not differentiate the properties of the obtained dough in comparison to those of the control dough. Higher concentrations of the infusions used showed a significant effect on the properties of the tested dough, especially the 5% infusion, because an improvement in stability was noted, but also an increase in dough softening.

In the studies of other authors [48], it was shown that adding green coffee extract up to 1.5% did not change the rheological properties of the wheat dough, similar to what was obtained in the discussed studies (Table 3). However, above the level of 1.5%, a significant decrease in water absorption, dough stability during mixing, and dough strength during kneading was observed [48]. In the discussed studies, the relationships were different (Table 3), because an increase in water absorption was noted (although an infusion was used, not an extract, which is not an exact comparative system), with unchanged or increased dough stability, but just like the cited authors [48], a decrease in dough strength was confirmed, because a greater softening of the dough was noted with an increase in the concentration of the added infusion based on the herb *G. hederacea* L. Cacak-Pietrzak et al. [4] confirmed that the addition of dandelion flowers increased the water absorption by the mixture of flour and additive, the dough development time and the dough stability during its kneading. In turn, other studies have shown that replacing wheat flour with powdered dandelion roots reduced the water absorption of such a mixture (in the range of 1–6%) and the dough's tolerance to mixing [49]. In turn, enriching wheat flour with powder from Moldavian dragonhead leaves increased water absorption, thus weakening the tolerance of dough to kneading [11]. The cited authors indicated higher fiber concentrations in the additives used as responsible for the increased water absorption of the tested systems, and at the same time interactions between the additive components—mainly fiber—and gluten proteins. Comparing the results of our own research (Table 3) with the results of the cited authors [4,11], it can be assumed that similar mechanisms contributed to greater dough softening with the addition of an infusion with a higher concentration of substances derived from the ground ivy herb. The observed changes in the rheological properties of the tested dough with the addition of *G. hederacea* L. were probably conditioned by the increased content of biologically active substances in the tested systems, and these could interact with gluten proteins, both at the stage of dough forming and the effect on gluten during dough mixing, thus increasing its softening. Studies by other authors [50] confirmed that the addition of tannins supported the aggregation of gluten proteins, modified the microstructure of gluten networks and improved mixing properties. Delcour et al. [51] showed that reducing agents, e.g., antioxidants, break disulfide bonds, thus reducing the size of protein macropolymers and weakening the gluten structure. The mechanisms cited could have occurred in the tested systems because additives with high concentrations of biologically active substances with antioxidant properties (including phenolic acids) were used. Studies by Kłosok et al. [52] showed that the structure and biochemical properties of the gluten network changed after adding phenolic acids to the model dough. The effect of

phenolic acids on the gluten network depends on the structure of the phenolic acid and the type of functional groups attached to the aromatic ring.

3.4. Laboratory Baking Parameters and Quality of Wheat Bread

Table 4 shows parameters related to laboratory baking of bread. Based on the results of the study, a statistically significant effect of enriching bread with an infusion of ground ivy of various concentrations on the volume and specific volume of bread was found.

Table 4. Bread baking process and quality parameters of tested breads with *G. hederacea* L. infusions.

Sample	Bread Baking Process			Quality Parameters of Bread			
	Dough Yield [%]	Oven Loss [%]	Bread Yield [%]	Loaf Volume [cm ³]	Specific Volume [cm ³ /g]	Moisture of Bread [%]	Crumb Porosity [%]
control	157.9 ^a ± 0.1	10.2 ^a ± 0.5	132.3 ^a ± 0.9	550 ^b ± 14	2.63 ^b ± 0.05	45.02 ^a ± 0.54	80 ^b ± 3
A	157.3 ^a ± 0.2	9.6 ^a ± 0.1	133.9 ^a ± 0.1	530 ^b ± 14	2.49 ^b ± 0.07	45.34 ^a ± 0.59	76 ^b ± 3
B	158.1 ^a ± 0.1	9.9 ^a ± 0.0	134.0 ^a ± 0.3	505 ^{a,b} ± 7	2.38 ^{a,b} ± 0.04	44.19 ^a ± 0.66	74 ^{a,b} ± 0
C	158.3 ^a ± 0.2	9.6 ^a ± 0.7	134.1 ^a ± 0.9	470 ^a ± 28	2.22 ^a ± 0.15	44.82 ^a ± 0.30	68 ^a ± 3

Mean values from three repetitions ± SD. Values in columns followed by the same superscript letters do not significantly differ at a significance level of 0.05.

It was found that the control and test samples did not differ statistically significantly in terms of all parameters of the baking process, i.e., dough yield, baking and bread yield. Dough yield ranged from 157.3% for the sample with a 1% infusion to 158.3% for the sample with a 5% infusion. Baking values ranged from 9.56% (C) to 10.23% (control bread), and bread yield ranged from 132.3% for the control sample to 134.1% for the sample with 5% infusion. In relation to the literature data, the calculated bread yield was lower in relation to the values given by Cacak-Pietrzak et al. [4]. According to the cited authors, bread containing dandelion flower powder achieved a bread yield value ranging from 143.5 to 147.0%. The cited authors observed the lowest bread yield for the control sample (143.0%), and the highest for the sample with the highest share of the tested plant additive. In turn, Wójcik et al. [53] noted lower values for baking bread enriched with nettle infusions, in the range of 7.1–8.4% in comparison to their own research (Table 4).

Replacing water with GH infusions had a statistically significant effect on most of the quality features of the tested wheat bread ($p < 0.05$) (Table 4). The increasing of GH infusion concentration caused a significant decrease in the loaf volume, specific volume and deterioration of the crumb porosity of the obtained bread. However, no effect of the *G. hederacea* L. infusion on the moisture content of the crumb of the tested bread was observed, which ranged from 45.34 to 44.19%. Meanwhile, the loaf volume ranged from 550 (control sample) to 470 cm³ (sample with 5% infusion). In a similar pattern, specific volume values were also recorded—from 2.63 for the control bread to 2.22 cm³/g for the bread with 5% GH infusion. This indicates a negative effect of higher concentration (3% or 5%) of infusions on the quality of the dough and the course of fermentation and baking. The observed dependence of the loaf volume on the concentration of GH infusions in the bread recipe is reflected in fermentographic studies (Table 2) and farinographic studies (Table 4), which also indicated a negative effect of infusions with a concentration above 1%. The volume of the loaf determined in our own study (Table 4) was larger (by approx. 100 cm³) than that obtained by Wójcik et al. [53] for breads with nettle infusions. The cited authors also confirm the unfavorable effect of increasing the infusion concentration on the volume of bread. In turn, Dziki et al. [11], for the tested wheat breads with the addition of *Dracocephalum moldavica* L. leaves powder, obtained loaf volumes 100 cm³ larger compared to our own studies (Table 4), but also observed a similar pattern of dependencies, a negative effect of the plant additive on the values of this parameter. The plant used to enrich bread by the cited authors (*Dracocephalum moldavica* L.) belongs to the same family in the botanical classification *Lamiaceae* as the ground ivy (*Glechoma hederacea* L.) used in our own studies. The reduction in the volume of bread under the influence of various plant additives was

also observed by other authors [2,4,12,13,54]. Plant raw materials enriching bread generally have an unfavorable effect on the volume of loaves. According to Cacak-Pietrzak et al. [4], the inclusion of non-gluten ingredients in wheat flour results in interactions between gluten proteins and the added ingredients. During kneading and dough rising, a loss of some proteins forming the gluten network is observed. As a result, the gases produced during fermentation are not fully retained by the weaker gluten network, which results in a small volume of bread. Moreover, phenolic compounds are also important, as they interact with thiol groups of gluten in wheat dough, weakening the gluten network that has been created. As a result, the volume of retained fermentation gases and the volume of bread after baking are reduced [55]. Moreover, bioactive components can affect yeast activity and thus the fermentation properties of flour (Table 2).

In the case of the porosity of the crumb of the tested bread, a significant effect was noted for the samples with 3 and 5% of the infusion, where the values of this parameter were 5 and 10% lower, respectively, compared to the control sample (80%). An inverse relationship to that observed in our own studies (Table 4) was shown by Cacak-Pietrzak et al. [54], as the porosity of the crumb of wheat bread increased with the increase in the share of *Cistus incanus* leaves powder. It was similar in the studies by Wójcik et al. [53] for the share of nettle infusion additions.

An important determinant of bread quality, especially in the context of consumer preferences, is the color of the product. The tested wheat breads, both the control and the breads enriched with the infusion of the herb *G. hederacea* L., were subjected to instrumental measurement of color parameters (crust and crumb). The results of the tests and calculations regarding the color of the tested breads are presented in Table 5. The appearance of the loaves and crumb is presented in Figure 2.

Table 5. Color parameters of tested breads with *G. hederacea* L. infusions.

Sample	L*	a*	b*	ΔE
crust				
control	57.19 ^a ± 6.21	13.60 ^b ± 0.96	30.29 ^b ± 2.96	-
A	59.12 ^a ± 4.27	12.78 ^b ± 1.44	31.67 ^b ± 1.23	2.51
B	57.62 ^a ± 3.31	12.28 ^b ± 1.72	30.06 ^b ± 1.16	1.41
C	58.27 ^a ± 3.13	10.17 ^a ± 1.26	27.51 ^a ± 1.99	5.81
crumb				
control	69.32 ^c ± 0.81	2.05 ^c ± 0.06	19.19 ^b ± 0.36	-
A	66.87 ^b ± 0.98	1.59 ^a ± 0.10	18.56 ^a ± 0.44	2.57
B	59.49 ^a ± 1.90	1.90 ^b ± 0.12	19.21 ^b ± 0.48	9.84
C	58.24 ^a ± 2.46	2.28 ^d ± 0.18	20.18 ^c ± 0.41	11.12

Mean values from three repetitions ± SD. Values in columns followed by the same superscript letters do not significantly differ at a significance level of 0.05.

According to the criterion established by the International Commission on Illumination (CIE), a total color difference ΔE between 0 and 2 is unrecognizable to an experienced observer, a color difference between 2 and 5 is recognizable, while a total color difference greater than 5 is significant and recognizable even by an inexperienced observer [11].

The crust color of the tested breads under the influence of GH infusions did not change significantly, only the use of the *G. hederacea* L. infusion with the highest concentration in the bread recipe resulted in a reduction in the redness and yellowness of the color of the obtained bread (C) in comparison with the other tested breads. Taking into account the total color difference (ΔE), it was found that the color of the crust of the tested bread with the addition of 3% of the infusion (B) was not different from the results obtained in the control sample, while in the case of bread with 1% infusion the color difference was noticeable. Only the crust of bread C had a different color in comparison with the control sample because the total color difference was greater than five. Greater color differentiation under the influence of the discussed additive was noted in the tests of the color of the bread

crumb. It was shown that the increasing concentration of the GH infusion used resulted in obtaining a product with a darker crumb. Moreover, the values of parameters a^* and b^* of the crumb of the tested breads were differentiated by the concentration of the *G. hederacea* L. infusion used. In the case of the infusion with the lowest concentration (1%), the difference in color was noticeable to the average observer ($\Delta E > 2$), while the color of the crumb of breads B and C with the infusion of higher concentrations (3 and 5%) was different from the color of the control bread. As it results from numerous studies related to the effect of the plant additive on the quality of wheat bread, the level of color change depends on the type of additive, including the chemical composition and water content and the size of its share in the recipe [11–13,54]. Pycia et al. [12,13] analyzed the effect of replacing flour with dried flowers and dried walnut leaves and usually found a decrease in the brightness of the crumb, i.e., a decrease in the value of the L^* parameter. Similarly, Cacak-Pietrzak et al. [4,49] observed that replacing part of the flour with powdered dandelion flowers and roots also resulted in a significant reduction in the brightness of the crumb of enriched bread. However, the color of the enriched product is mainly a derivative of the type and amount of dye present in the enriching additive. This is confirmed by studies by other authors [11–13,55–57].

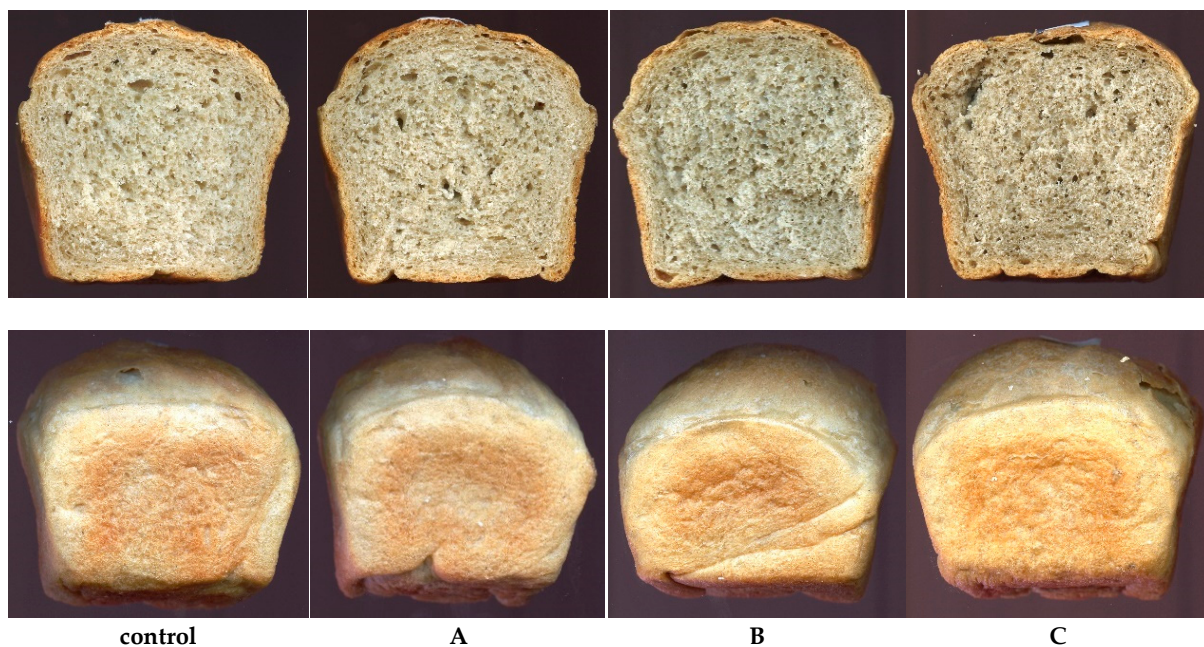


Figure 2. Appearance of loaves and their cross-sections of tested breads with *G. hederacea* L. infusions: **control**—bread made of dough with water; **A**—bread made of dough with 1% infusion; **B**—bread made of dough with 3% infusion; **C**—bread made of dough with 5% infusion.

Table 6 presents the results of crumb texture parameter measurements of the tested types of wheat bread. The texture of bread crumb and its volume are parameters that significantly affect consumer acceptance [4]. The values of these parameters are influenced by recipe ingredients, and the course of the fermentation and baking processes [58].

Table 6. Results of crumb texture parameters (TPA test) of tested breads with *G. hederacea* L. infusions.

Sample	Hardness [N]	Springiness [-]	Chewiness [N]	Cohesiveness [-]
control	7.35 ^a ± 1.91	0.75 ^b ± 0.03	3.58 ^a ± 0.78	0.65 ^b ± 0.02
A	8.47 ^a ± 2.05	0.69 ^a ± 0.01	3.61 ^a ± 0.85	0.62 ^{a,b} ± 0.01
B	8.97 ^a ± 0.49	0.69 ^a ± 0.03	3.85 ^a ± 0.33	0.63 ^{a,b} ± 0.02
C	9.05 ^a ± 1.20	0.70 ^a ± 0.02	3.95 ^a ± 0.66	0.62 ^a ± 0.02

Mean values from five repetitions ± SD. Values in columns followed by the same superscript letters do not significantly differ at a significance level of 0.05.

The evaluation of crumb texture parameters of the tested wheat bread (Table 6) showed that the share of ground ivy infusions at concentrations of 1, 3 and 5% had no significant effect on the hardness and chewiness of the crumb compared to the control sample. Only a statistically significant effect was shown on the elasticity and cohesiveness of the crumb ($p < 0.05$). The bread tested with the infusions had a crumb that was less elastic and more compact, as evidenced by lower values of the elasticity and cohesiveness parameters (by approx. 0.05 units) compared to the control sample. Similar relationships within the crumb texture parameters were also observed by other authors [4,11,53,54]. According to Xu et al. [58], the hardness of the crumb generally decreases with the decrease in the volume of bread loaves. This phenomenon may be related to the presence of phenolic compounds that affect the volume of bread [59,60], as the cited authors found a reduction in the volume of loaves under the influence of ferulic acid.

3.5. Health-Promoting Properties of Wheat Bread with Addition of *G. hederacea* Infusion

Glechoma hederacea L. is a medicinal herb rich in polyphenols, including several bioactive compounds with anticancer, anti-inflammatory, antibacterial and antiviral properties, such as phenolic acid derivatives and flavonoids [61–65]. The results of the total phenolics content (TPC) and the total flavonoid content (TFC) assays as well as the antioxidant activity of bread with ground ivy infusion of varying concentrations using ABTS and FRAP methods are detailed in Tables 7 and 8.

Table 7. The contents of total phenolics and flavonoids of wheat bread with *G. hederacea* L. infusion.

Sample	Total Phenolic Content (TPC) [mg GAE/100 g d.w.]	Total Flavonoid Content (TFC) [mg QE/100 g d.w.]
control	21.39 ^a ± 0.61	1.49 ^a ± 0.01
A	30.47 ^b ± 2.53	2.52 ^b ± 0.01
B	52.44 ^c ± 0.86	5.09 ^c ± 0.01
C	65.50 ^d ± 4.07	8.60 ^d ± 0.04

Mean values from two repetitions ± SD. Values in columns followed by the same superscript letters do not significantly differ at a significance level of 0.05. Abbreviations: GAE, equivalent of gallic acid; QE, equivalent of quercetin.

Table 8. Antioxidant activity of wheat bread with *G. hederacea* L. infusion.

Sample	ABTS	FRAP
	mMol TE/100 g d.w.	
control	470.58 ^a ± 9.06	47.68 ^a ± 2.06
A	562.09 ^b ± 1.35	69.35 ^b ± 0.36
B	708.29 ^c ± 1.35	127.15 ^c ± 5.85
C	743.07 ^d ± 3.50	150.49 ^d ± 0.04

Mean values from two repetitions ± SD. Values in columns followed by the same superscript letters do not significantly differ at a significance level of 0.05. Abbreviations: ABTS and FRAP—methods of measuring antioxidant activity; TE, equivalent of Trolox.

The TPC and TFC, as well as the antioxidant power of bread, increased as the concentration of ground ivy infusion rose. The TPC and TPF ranged from 21.39 ± 0.61 to 65.50 ± 4.07 mg GAE/100 g d.w. and 1.49 ± 0.01 to 8.60 ± 0.04 mg QE/100 g d.w., respectively. Incorporating 5% infusion (C) into the dough led to a significant increase in the TPC and TFC, with the TPC showing a 306% rise and the TFC a 577% increase compared to the control samples. The values for ABTS and FRAP assays ranged from 470.58 ± 9.06 to 743.07 ± 3.50 and 47.68 ± 2.06 mmol TE/100 g d.w. to 150.49 ± 0.04 mmol TE/100 g d.w. Thus, the antioxidant potential increased by 158% as measured by the ABTS method, and by 316% according to the FRAP assay, in the bread with addition of *G. hederacea* 5% infusion (C), compared to the control samples. This trend of enhanced TPC and TPF parameters and antioxidant properties has been documented by other researchers who added various

herbal ingredients to wheat bread [66–70]. Dziki et al. [66] studied the effect of the addition of dried and powdered parsley leaves to wheat flour on the antioxidant properties of wheat bread. This type of bread exhibited nearly twice the number of phenolic compounds and demonstrated improved antioxidant activity compared to the control bread. Similarly, in the study of Skende et al. [67], aromatic plants enhanced the levels of bioactive and antioxidant compounds in the bread. Their results showed that the inclusion of 1% dry oregano, thyme or *Satureja* in the bread recipe increased 28.0, 26.3 and 24.7-fold TPC, respectively. The addition of the plants led to higher antioxidant power against DPPH and ABTS, as well as in reducing capacity, using FRAP. Das et al. [68] investigated the antioxidant properties of wheat breads enriched with coriander leaf powder. Their results indicated a significant enhancement in both FRAP and DPPH radical scavenging activity in the enriched breads. Earlier, Raba et al. [69] experimented with different ratios of sweet basil to enrich bread. Their findings revealed that the ingredient enhanced the antioxidant capacity of the bread. Specifically, TPC increased from 0.19 to 0.28 mM GAE/100 g in bread flavored with basil. For comparison, the polyphenol level in the control sample was 0.18 mM GAE/100 g. Instead, Wójcik et al. [70] pointed out that the incorporation of mixed herbs infusion into the wheat flour strongly enhanced the antioxidant power of the bread without decreasing its quality parameters; on the contrary, the bread with the addition of herbal infusion increased the volume of the final product and decreased hardness and chewiness, compared to the bread prepared with dried herbs.

The identification of specific phenolic compounds in alcoholic extracts of the bread was conducted using Ultra-Performance Liquid Chromatography with Photodiode Array Detection and Mass Spectrometry (UPLC-PDA-MS/MS). Tentative identification of the compounds was performed by comparing their retention times, elution sequences, UV–Vis, and mass spectra with data from the existing literature [61–65]. All spectroscopic, spectrometric and chromatographic details are provided in Table 9.

From a qualitative point of view, the bread fortified with ground ivy infusion was richer in bioactive compounds compared to the control bread. Products with an addition of infusion at 3 and 5% contained 11 phenolic compounds with a higher concentration than that found in the control bread; bread with a 1% infusion added contained 9 such components. Among the identified constituents, rutin and kaempferol 3-O-robinbioside were found in the highest concentrations, which is in agreement with studies of other authors, who reported quercetin and kaempferol derivatives as one of the most abundant components in *G. hederacea* phenolic profile [61–65]. The average total content of the detected compounds was ca. 20, 50 and 100 times higher for bread with an infusion concentration of 1, 3 and 5%, respectively, than for the product with no infusion addition. This makes the fortified bread highly appealing for health promotion.

The infusion of ground ivy has a large application potential due to the profile and content of bioactive substances. Therefore, bread enriched with ground ivy can be an excellent option for consumers seeking natural, health-boosting ingredients. The presented research results prove that it significantly increases the antioxidant potential of bread. Moreover, it offers a range of medicinal properties, i.e., anti-inflammatory, respiratory and digestive health benefits [22,23]. The inclusion of flavorful herbs like ground ivy can also reduce the need for excess salt, sugar or unhealthy fats in bread recipes. This could make the bread a healthier option, especially for people looking to reduce their intake of sodium or added sugars. Taking into account the promising results of research on the use of infusions from ground ivy for bread production, research is planned to enrich other bakery products with this additive, i.e., rolls and croissants. Due to the growing popularity of other ready-made flour products such as tortillas, burger rolls and pasta, these products can also be a matrix for enrichment with infusions based on the *Glechoma hederacea* L. herb.

Table 9. Individual phenolic compounds identified by UPLC-PDA-MS/MS in bread with *G. hederacea* L. infusion.

No.	Compound	Rt	$\lambda_{\max}$	[M – H] [–] <i>m/z</i>		Content			
						Control	A	B	C
		min	nm	MS	MS/MS	$\mu\text{g}/\text{g d.w.}$			
1	Chlorogenic acid	2.93	299 sh, 324	353	191	n.d.	n.d.	33.71 ^a ± 0.30	84.66 ^a ± 0.74
2	Cryptochlorogenic acid	3.05	299 sh, 324	353	191	n.d.	20.22 ^b ± 0.18	100.68 ^c ± 0.88	223.50 ^b ± 1.96
3	Caffeoylthreonic acid	3.37	299 sh, 324	297	179	1.06 ^a ± 0.01	49.95 ^c ± 0.44	154.27 ^b ± 1.36	298.43 ^d ± 2.62
4	Rutin	4.43	255,352	609	301	n.d.	614.61 ^h ± 5.40	1505.64 ⁱ ± 13.22	2597.33 ^h ± 22.81
5	Hyperoside	4.62	253, 350	463	301	n.d.	112.42 ^e ± 0.99	234.04 ^e ± 2.06	467.41 ^c ± 4.11
6	Quercetin 3- <i>O</i> -(6''-malonylhexoside	4.89	255, 347	549	301	n.d.	79.70 ^d ± 0.70	289.13 ^f ± 2.54	485.39 ^c ± 4.26
7	Kaempferol 3- <i>O</i> -robinbioside	4.95	262, 341	593	285	56.61 ^c ± 0.50	400.08 ^g ± 3.51	834.99 ^h ± 7.33	1521.45 ^g ± 13.36
8	Vitexin 2''- <i>O</i> -rhamnoside	5.18	267, 333	577	293	n.d.	44.83 ^a ± 0.39	122.57 ^d ± 1.08	232.45 ^b ± 2.04
9	Rosmarinic acid	5.60	329	359	161	21.36 ^b ± 0.19	128.61 ^f ± 1.13	536.08 ^g ± 4.71	990.58 ^f ± 8.70
10	Apigenin	6.11	267, 331	269	225	n.d.	n.d.	36.00 ^a ± 0.32	93.41 ^a ± 0.82
11	3- <i>O</i> -methyl-rosmarinic acid	6.73	328	373	179	n.d.	43.60 ^a ± 0.38	159.17 ^b ± 1.39	332.62 ^e ± 2.91
	Total					79.03 ± 0.69	1493.99 ± 13.12	4006.27 ± 35.19	7674.97 ± 67.42

Mean values from two repetitions ± SD. Values in columns followed by the same superscript letters do not significantly differ at a significance level of 0.05. Abbreviations: Rt, retention time; [M – H][–], negative ion values; *m/z*, mass-to-charge ratio; d.w., dry weight; n.d., not detected.

4. Conclusions

In this study, an attempt was made to enrich wheat bread with an infusion based on dried ground ivy herb. The conducted research is innovative from the point of view of studies on the usefulness of various plant raw materials that can potentially improve the health-promoting properties of bread. The obtained research results provide a lot of information related to the effect of GH infusion on the fermentation properties of flour and the quality of bread, including the content of bioactive components in the finished product. It was found that replacing water with ground ivy infusions of various concentrations (1, 3, 5%) affected the fermentation properties of flour, the values of flour and dough parameters determined using a farinograph and the quality, including the health-promoting properties of bread. The fermentation properties of wheat flour deteriorated, because the samples containing GH infusion were characterized by a smaller volume of CO₂ produced and carbon dioxide released outside the dough and retained in the dough. The water absorption of the flour and the dough development time increased with the increase in the infusion concentration. In turn, the dough stability did not change nor was it extended under the influence of *G. hederacea* L. infusions, but at the same time, an increase in dough softening was noted. The GH infusion had an adverse effect on the volume of bread and the color of the crumb. Nevertheless, the infusion of ground ivy improved the antioxidant potential of bread and the content of total polyphenols. UPLC analysis allowed the identification of 11 phenolic compounds, among which rutin dominated. This indicates the probable pro-health potential of bread enriched with the infusion of the ground ivy herb.

Therefore, the infusion of ground ivy is an interesting additive enriching wheat bread in terms of bioactive substances. However, replacing water in the recipe with a GH infusion with a concentration of 3% may be a compromise between technological parameters and pro-health values from a technological point of view. In the future, research should also be undertaken related to the sensory and consumer evaluation of the obtained bread, because its results are not only necessary to determine the level of ground ivy addition but also crucial for the consumer acceptance of the new product.

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