

Article

The Influence of Different Polyphenols on the Digestibility of Various Kinds of Starch and the Value of the Estimated Glycemic Index

Dominika Kwaśny ^{1,*} , Barbara Borczak ^{1,*} , Joanna Kapusta-Duch ¹  and Ivan Kron ² 

¹ Department of Human Nutrition and Dietetics, Faculty of Food Technology, University of Agriculture in Kraków, Aleja Mickiewicza 21, 31-120 Kraków, Poland

² Department of Chemistry, Biochemistry, Clinical Biochemistry and LABMED a.s., Faculty of Medicine, University of Pavol Jozef Safarik in Kosice, 041 80, Šrobárova 1014/2, 040 01 Košice, Slovakia

* Correspondence: dominika.kwasny@student.urk.edu.pl (D.K.); barbara.borczak@urk.edu.pl (B.B.); Tel.: +48-12-662-48-19 (D.K.); +48-12-662-48-15 (B.B.)

Featured Application: This research has contributed to a greater understanding of the influence of polyphenols on starch digestibility and its glycemic index. This may ultimately facilitate the development of traditional starchy products, such as bread, with a reduced glycemic index without compromising their organoleptic characteristics (e.g., color, taste, aroma, and texture).

Abstract: Considering the prevalence of diet-related diseases, new ways of preventing them are being sought. One of them is the addition of polyphenols to high-starch products to inhibit their digestibility and reduce their glycemic index. Therefore, this study aimed to investigate the differences between polyphenols popular in food ((+)catechin, epigallocatechin gallate, quercetin, kaempferol, naringenin, hesperidin, *trans*-ferulic acid, and *p*-coumaric acid), in terms of their impact on wheat, rice, potato, and maize starch digestibility. Polyphenols were added to starch separately, before and after its pasting, in one of the following doses: 5, 10, and 20 mg. Starch was digested in the presence of single polyphenols to measure RDS (rapidly digestible starch), SDS (slowly digestible starch), RS (resistant starch), and TS (total starch) content. On that basis, the SDI (starch digestion index) was calculated, and the GI (glycemic index) was estimated. The results show that polyphenols inhibit starch digestion at different levels depending on the type of tested starch and the time of polyphenol addition. However, in terms of RDS, TS, and eGI (estimated glycemic index), the greatest impact was observed for epigallocatechin gallate in a dose of 20 mg most frequently, independently of the kind of tested starch and the time of polyphenol addition.

Keywords: starch digestibility; polyphenol; glycemic index; inhibitory activity; molecular structure; epigallocatechin gallate



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1. Introduction

Non-communicable diseases (NCDs) are today the leading causes of death around the world. One of the four major NCDs is diabetes, while more than 90% of diabetes cases are type 2 diabetes. Furthermore, diabetes and obesity may lead to all other diet-related chronic diseases [1–6]. One of the risk factors for the development of type 2 diabetes is an intake of products/meals with a high glycemic index that leads to raised blood glucose levels [5,7]. Carbohydrates, predominantly complex ones (starch), should comprise 40–70% of the total daily energy requirement [8]. At the same time, most of the starchy foods (e.g., wheat breadstuff), which underlie our regular diet, exhibit a high glycemic index [9]. It is impossible to make an accurate assessment of the calories provided by a specific glycemic carbohydrate component based on its quantity alone due to variations in both the rate and

extent of its digestion and absorption [10]. Hence, the rate and extent of starch digestion are important in controlling postprandial blood sugar [11].

One of the ways to minimize the risk of type 2 diabetes or expand the scope of foods acceptable to eat by people already suffering from this disease is to provide food rich in natural bioactive ingredients, e.g., polyphenols. Polyphenols are known to inhibit starch digestibility through two mechanisms: interactions with α -amylase and interactions with amylose [12]. The action of α -amylase consists of bonding the hydroxyl groups with the active site of the enzyme and making the hydrophobic interactions between the aromatic groups of polyphenols and the enzyme [13]. The second mechanism of inhibition of starch digestibility is also grounded on hydroxyl bonding and hydrophobic interactions between polyphenols and amylose, and as an effect, non-digestible complexes are built [14]. There have already been studies that tested various products enriched with whole/parted fruits or polyphenol extracts and their effect on inhibiting the digestibility of starch in vitro [15–21]. The mentioned research showed the retarding activity of polyphenol-enriched products on starch digestion. However, whole/parted fruits contain not only polyphenols but also other bioactive compounds, e.g., fiber, which can have an impact on starch digestibility or its properties. In terms of polyphenol extracts, they have an unknown composition and could be mixtures of different polyphenols in different doses. Studies were also conducted to examine the impact of single polyphenols on starch digestibility [22–36]. Although these studies tested single polyphenols in a pure form, they differ from each other in the applied experimental conditions and features of the reagents that were used, so it is impossible to compare their results. A pilot study was also carried out [37]. However, the results only indicated differences in the amount of one starch fraction (resistant starch) and only in wheat starch.

Thus, the results already obtained do not give a clear answer to the question of which polyphenols have the strongest inhibiting effect on starch digestibility and, at the same time, lower glycemic index. The present research was conducted to fill the information gap in the literature. The chosen phenolic compounds were commonly found in popular food raw materials and starches and are most widely used in the manufacture of high-starch products. The objectives of the proposed research were (i) to determine whether there were differences between different polyphenols in the reduction in starch digestibility and glycemic index and (ii) to find the most effective phenolic compound in this respect.

2. Materials and Methods

2.1. Preparation of Starch–Phenolic Complexes

A total of 5% *w/v* (25 mg in 475 μ L of distilled water) wheat, rice, potato, and maize starch (Sigma Aldrich, S5127, St. Louis, MO, USA; Sigma Aldrich, S7260, St. Louis, MO, USA; Chempur, Piekary Śląskie, Poland; Biomus, Lublin, Poland, respectively) gels were prepared. The starches were weighed in screw-cap tubes, mixed with the appropriate amount of distilled water, and incubated in a water bath with a shaker (ELPIN 357, Łódź, Poland) at 90 °C for 30 min to gelatinize. The mixture was then cooled to 37 °C for a further 30 min by leaving it at room temperature without access to light. In addition to starch, two polyphenols from four different groups were chosen: (+)catechin hydrate (Sigma Aldrich 22110, St. Louis, MO, USA) and epigallocatechin gallate (Sigma Aldrich PHR1333, St. Louis, MO, USA) (flavanols), quercetin (Sigma Aldrich Q4951, St. Louis, MO, USA) and kaempferol (Sigma Aldrich K0133, St. Louis, MO, USA) (flavonols), naringenin (Sigma Aldrich N5893, St. Louis, MO, USA) and hesperidin (Sigma Aldrich H5254, St. Louis, MO, USA) (flavanones), and *trans*-ferulic acid (Sigma Aldrich 128708, St. Louis, MO, USA) and *p*-coumaric acid (Sigma Aldrich C9008, St. Louis, MO, USA) (phenolic acids). Each of the compounds mentioned above was added separately to the starch, before (first the addition of polyphenol to the starch took place, then the gelatinization of the starch, and finally cooling of the samples to 37 °C) and after making gels (first the gelatinization of the starch took place, then cooling of the samples to 37 °C, and finally the addition of polyphenol to the starch), in the following doses: 5, 10, and 20 mg. Before adding to

the starch, polyphenols were dissolved directly in 0.5 mL of dimethyl sulfoxide (DMSO) (Chempur, Piekary Śląskie, Poland).

2.2. Methods

2.2.1. Measurement of RDS, SDS, RS, and TS Contents

The moisture percentage was determined using the oven-drying method (AOAC 940.26) with a laboratory dryer (SML 30/250, Zalmed, Warszawa, Poland). Rapidly digestible starch (RDS), slowly digestible starch (SDS), resistant starch (RS), and total starch (TS) contents were determined using commercial kits (Megazyme International Ireland, Bray Business Park, Bray, Co., Wicklow, Ireland) with the application of AOAC standards [38,39]. In summary, the samples were incubated in a shaking water bath (MEMMERT WNE 14, Schwabach, Germany) with a mixture of pancreatic α -amylase and amyloglucosidase (PAA (40 KU/g)/AMG (17 KU/g)) in maleate buffer, pH 6.0, at 37 °C for up to 4 h with continual stirring to hydrolyse the starch into *D*-glucose. A total of 1.0 mL of aliquots of the reaction solution was removed at 20, 120, 180, and 240 min. To terminate the reaction, the aliquots were transferred to 20 mL of 50 mM acetic acid. These solutions were thoroughly mixed, and 0.1 mL aliquots were incubated with 0.1 mL of AMG (100 U/mL) to hydrolyse the remaining traces of maltose to glucose, which were measured with glucose oxidase/peroxidase reagent (GOPOD) on a spectrophotometer (SPECORD 40, Analytik Jena GmbH, Jena, Germany) at 510 nm. To measure RS, a 4 mL aliquot was removed from the stirring solution after 240 min, added to 4 mL of aqueous ethanol (50% *v/v*), and thoroughly mixed. The samples were centrifuged (MPW MED. INSTRUMENTS 351e, Warszawa, Poland), and the pellet was washed with aqueous ethanol to remove free glucose and then suspended in sodium hydroxide to dissolve RS. The solution was neutralised, starch was hydrolysed to glucose with AMG, and the glucose was measured with a GOPOD reagent. All values were calculated based on dry matter ($\text{g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$).

2.2.2. Calculation of SDI and Estimation of GI

Finally, the starch digestion index ($\text{SDI} = (\text{RDS} \times \text{TS}^{-1}) \times 100$) was calculated based on the received data.

The following formula was used to calculate the hydrolysis rate (%):

$$\text{Hydrolysis rate (\%)} = \text{Gt} \times 0.9 / \text{starch content (mg)} \quad (1)$$

Gt—glucose concentration (mg/0.1 mL).

0.9—factor conversion from glucose to starch.

White wheat bread previously freeze-dried was used as a reference sample for eGI (estimated glycemic index) calculation. The sample hydrolysis index (HI) was the percentage of the area under the hydrolysis curve (AUC) of each sample and that of white wheat bread, and (eGI) was determined as follows [40]:

$$\text{eGI} = 39.71 + 0.549\text{HI} \quad (2)$$

2.3. Data Analyses

The results were presented as ranges of at least three parallel repetitions with a standard deviation around the mean. Multivariate analysis of variance was used to assess the impact of various polyphenolic compounds and doses on the RDS, SDS, RS, TS content, SDI value, and GI estimation. The significance of the differences was tested using the Duncan test at a level of $p < 0.05$. All calculations were performed using Statistica v.13 software (Statsoft, Inc., Tulsa, OK, USA).

3. Results

3.1. Dry Matter Content

The dry matter content of the tested samples was $4.54 \pm 0.1\%$ (wheat starch), $5.07 \pm 0.2\%$ (rice starch), $4.96 \pm 0.4\%$ (potato starch), $4.88 \pm 0.2\%$ (maize starch), and $94.96 \pm 0.1\%$ (freeze-dried bread).

3.2. Wheat Starch

In the study of wheat starch digestibility (polyphenol addition prior to starch gelatinization), the lowest values of RDS and TS were observed with the addition of epigallocatechin gallate (20 mg) ($19.49 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$ for both parameters, $p < 0.05$, Table 1). Regarding SDS, RS, and SDI, the addition of kaempferol (10 mg) was the most effective ($30.78 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $1.38 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $63.65 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, respectively, $p < 0.05$, Table 1, Figure 1a).

Table 1. Rapidly digestible starch (RDS), slowly digestible starch (SDS), resistant starch (RS), total starch (TS), starch digestion index (SDI), and estimated glycemic index (eGI) values ($\text{g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$) in wheat starch (polyphenol addition prior to starch gelatinization) depending on the type and dose of the added polyphenol standard.

		RDS	SDS	RS	TS	SDI	eGI
Wheat starch with the addition of							
(+)catechin	5 mg	$99.80 \pm 0.0^{\text{n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$99.80 \pm 0.0^{\text{f,g,h}}$	$100.00 \pm 0.0^{\text{ij}}$	$94.60 \pm 0.0^{\text{j,k,l}}$
	10 mg	$97.65 \pm 0.6^{\text{ij,k}}$	$0.80 \pm 1.1^{\text{b}}$	$0.39 \pm 0.6^{\text{b,c}}$	$98.84 \pm 1.1^{\text{f,g,h}}$	$98.80 \pm 1.7^{\text{g,h}}$	$94.48 \pm 2.4^{\text{j,k}}$
	20 mg	$98.92 \pm 0.4^{\text{l,l,m,n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.71 \pm 0.1^{\text{d,e,f}}$	$99.63 \pm 0.3^{\text{f,g,h}}$	$99.29 \pm 0.1^{\text{g,h,lj}}$	$91.81 \pm 1.2^{\text{f}}$
epigallocatechin gallate	5 mg	$58.48 \pm 0.2^{\text{c}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$58.48 \pm 0.2^{\text{c}}$	$100.00 \pm 0.0^{\text{ij}}$	$72.34 \pm 0.0^{\text{c}}$
	10 mg	$37.41 \pm 0.7^{\text{b}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$37.41 \pm 0.7^{\text{b}}$	$100.00 \pm 0.0^{\text{ij}}$	$60.56 \pm 0.0^{\text{b}}$
	20 mg	$19.49 \pm 0.1^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$19.49 \pm 0.1^{\text{a}}$	$100.00 \pm 0.0^{\text{ij}}$	$50.59 \pm 0.0^{\text{a}}$
hesperidin	5 mg	$93.80 \pm 0.0^{\text{g}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$96.22 \pm 0.0^{\text{e}}$	$97.48 \pm 0.0^{\text{e}}$	$91.87 \pm 0.0^{\text{f}}$
	10 mg	$95.83 \pm 1.1^{\text{h}}$	$1.61 \pm 0.0^{\text{c}}$	$0.0 \pm 0.0^{\text{a}}$	$99.85 \pm 0.0^{\text{g,h}}$	$95.97 \pm 1.1^{\text{d}}$	$94.13 \pm 0.2^{\text{j,k}}$
	20 mg	$97.33 \pm 0.4^{\text{ij}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$98.96 \pm 0.4^{\text{f,g,h}}$	$98.36 \pm 0.0^{\text{f,g}}$	$93.30 \pm 0.0^{\text{g,h,ij}}$
naringenin	5 mg	$98.31 \pm 0.0^{\text{j,k,l,l,m}}$	$0.0 \pm 0.0^{\text{a}}$	$0.97 \pm 0.0^{\text{f}}$	$99.28 \pm 0.0^{\text{f,g,h}}$	$99.02 \pm 0.0^{\text{g,h,i}}$	$94.85 \pm 0.0^{\text{k,l}}$
	10 mg	$99.40 \pm 0.0^{\text{m,n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.59 \pm 0.0^{\text{c,d}}$	$99.99 \pm 0.0^{\text{h}}$	$99.41 \pm 0.0^{\text{h,lj}}$	$93.55 \pm 0.0^{\text{h,ij,k}}$
	20 mg	$98.00 \pm 0.0^{\text{j,k,l,l}}$	$0.0 \pm 0.0^{\text{a}}$	$0.59 \pm 0.0^{\text{c,d}}$	$98.59 \pm 0.0^{\text{f}}$	$99.40 \pm 0.0^{\text{h,lj}}$	$92.68 \pm 0.0^{\text{f,g,h,i}}$
trans-ferulic acid	5 mg	$91.92 \pm 0.7^{\text{f}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$94.22 \pm 0.7^{\text{d}}$	$97.56 \pm 0.0^{\text{e,f}}$	$92.12 \pm 0.0^{\text{f,g}}$
	10 mg	$98.60 \pm 0.3^{\text{k,l,l,m}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$98.60 \pm 0.3^{\text{f}}$	$100.00 \pm 0.0^{\text{ij}}$	$94.03 \pm 0.0^{\text{j,k}}$
	20 mg	$99.21 \pm 0.3^{\text{m,n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.0 \pm 0.0^{\text{a}}$	$99.21 \pm 0.3^{\text{f,g,h}}$	$100.00 \pm 0.0^{\text{ij}}$	$94.03 \pm 0.0^{\text{j,k}}$
p-coumaric acid	5 mg	$98.90 \pm 0.0^{\text{l,l,m,n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.68 \pm 0.0^{\text{d,e}}$	$99.59 \pm 0.0^{\text{f,g,h}}$	$99.31 \pm 0.0^{\text{g,h,lj}}$	$95.75 \pm 0.0^{\text{l}}$
	10 mg	$98.78 \pm 0.0^{\text{k,l,l,m,n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.76 \pm 0.0^{\text{d,e,f}}$	$99.54 \pm 0.0^{\text{f,g,h}}$	$99.23 \pm 0.0^{\text{g,h,lj}}$	$93.75 \pm 0.0^{\text{ij,k}}$
	20 mg	$98.99 \pm 0.0^{\text{l,m,n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.76 \pm 0.0^{\text{d,e,f}}$	$99.75 \pm 0.0^{\text{f,g,h}}$	$99.23 \pm 0.0^{\text{g,h,lj}}$	$93.75 \pm 0.0^{\text{ij,k}}$
quercetin	5 mg	$91.40 \pm 0.1^{\text{f}}$	$7.88 \pm 0.0^{\text{d}}$	$0.68 \pm 0.0^{\text{d,e}}$	$99.96 \pm 0.1^{\text{h}}$	$91.44 \pm 0.0^{\text{c}}$	$92.12 \pm 0.0^{\text{f,g}}$
	10 mg	$96.80 \pm 1.1^{\text{h,i}}$	$0.0 \pm 0.0^{\text{a}}$	$0.19 \pm 0.0^{\text{a,b}}$	$96.99 \pm 1.1^{\text{e}}$	$99.80 \pm 0.0^{\text{h,lj}}$	$92.38 \pm 0.0^{\text{f,g,h}}$
	20 mg	$94.55 \pm 1.0^{\text{g}}$	$0.0 \pm 0.0^{\text{a}}$	$0.38 \pm 0.0^{\text{b,c}}$	$94.93 \pm 1.0^{\text{d}}$	$99.60 \pm 0.0^{\text{h,ij}}$	$91.53 \pm 0.0^{\text{f}}$
kaempferol	5 mg	$97.78 \pm 0.1^{\text{ij,k,l}}$	$0.0 \pm 0.0^{\text{a}}$	$0.94 \pm 0.0^{\text{e,f}}$	$98.72 \pm 0.1^{\text{f,g}}$	$99.05 \pm 0.0^{\text{g,h,ij}}$	$93.75 \pm 0.0^{\text{ij,k}}$
	10 mg	$61.57 \pm 0.4^{\text{d}}$	$30.78 \pm 0.2^{\text{f}}$	$1.38 \pm 0.0^{\text{g}}$	$96.74 \pm 0.6^{\text{e}}$	$63.65 \pm 0.0^{\text{a}}$	$88.10 \pm 0.0^{\text{d}}$
	20 mg	$72.63 \pm 0.9^{\text{e}}$	$26.27 \pm 0.3^{\text{e}}$	$0.85 \pm 0.0^{\text{d,e,f}}$	$99.76 \pm 1.2^{\text{f,g,h}}$	$72.81 \pm 0.0^{\text{b}}$	$90.01 \pm 0.0^{\text{e}}$
Wheat starch without the addition of polyphenols		$98.97 \pm 0.0^{\text{l,m,n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.78 \pm 0.0^{\text{d,e,f}}$	$99.75 \pm 0.0^{\text{f,g,h}}$	$99.22 \pm 0.0^{\text{g,h,lj}}$	$94.67 \pm 0.0^{\text{k,l}}$

The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters in columns differ significantly at $p < 0.05$. * values in bold are the lowest (RDS, TS, SDI, and eGI) or highest (SDS, RS) in columns.

In the case of the polyphenol addition after wheat starch gelatinization, epigallocatechin gallate (20 mg) was found to be the most effective in lowering RDS, TS, and SDI values ($26.82 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $34.89 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, and $76.88 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, respectively,

$p < 0.05$, Table 2, Figure 1b). The highest SDS value was observed when naringenin (20 mg) was added to the starch ($14.09 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $p < 0.05$, Table 2). The highest values of RS were observed when hesperidin (10 mg) and quercetin (5 mg) were added to the starch ($3.31 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$ and $3.33 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, respectively, $p < 0.05$, Table 2).

Table 2. RDS, SDS, RS, TS, SDI, and eGI values ($\text{g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$) in wheat starch (polyphenol addition after starch gelatinization), depending on the type and dose of the added polyphenol standard.

		RDS	SDS	RS	TS	SDI	eGI
Wheat starch with the addition of							
(+)catechin	5 mg	$95.45 \pm 0.4^{\text{f}}$	$0.4 \pm 0.6^{\text{a,b}}$	$0.68 \pm 0.1^{\text{c,d}}$	$97.73 \pm 0.6^{\text{ij,k}}$	$97.67 \pm 0.0^{\text{l,t}}$	$96.88 \pm 0.2^{\text{t}}$
	10 mg	$93.4 \pm 0.3^{\text{f}}$	$2.37 \pm 1.1^{\text{d}}$	$1.75 \pm 0.0^{\text{ij}}$	$99.10 \pm 1.4^{\text{l,j,m}}$	$94.25 \pm 1.1^{\text{f}}$	$96.82 \pm 0.0^{\text{t}}$
	20 mg	$94.24 \pm 0.4^{\text{f}}$	$4.79 \pm 0.0^{\text{f}}$	$0.59 \pm 0.7^{\text{c}}$	$99.62 \pm 0.1^{\text{m}}$	$94.6 \pm 0.3^{\text{f,g}}$	$97.50 \pm 0.0^{\text{u}}$
epigallocatechin gallate	5 mg	$61.2 \pm 0.8^{\text{c}}$	$6.28 \pm 0.1^{\text{g}}$	$0.38 \pm 0.0^{\text{b}}$	$69.43 \pm 0.9^{\text{c}}$	$88.15 \pm 0.0^{\text{d}}$	$77.56 \pm 0.0^{\text{c}}$
	10 mg	$40.98 \pm 0.1^{\text{b}}$	$3.94 \pm 0.0^{\text{e}}$	$1.64 \pm 0.9^{\text{i}}$	$46.56 \pm 0.1^{\text{b}}$	$88.01 \pm 0.0^{\text{d}}$	$64.93 \pm 0.0^{\text{b}}$
	20 mg	$26.82 \pm 0.1^{\text{a}}$ *	$6.31 \pm 0.0^{\text{g}}$	$0.97 \pm 0.0^{\text{f,g}}$	$34.89 \pm 0.1^{\text{a}}$	$76.88 \pm 0.0^{\text{a}}$	$57.90 \pm 0.0^{\text{a}}$
hesperidin	5 mg	$93.38 \pm 0.1^{\text{i}}$	$0.0 \pm 0.0^{\text{a}}$	$2.43 \pm 1.1^{\text{f}}$	$95.81 \pm 0.1^{\text{g}}$	$97.46 \pm 0.1^{\text{k,l,j}}$	$92.05 \pm 0.0^{\text{h}}$
	10 mg	$92.45 \pm 0.1^{\text{h}}$	$1.54 \pm 0.0^{\text{c}}$	$3.31 \pm 0.6^{\text{n}}$	$97.29 \pm 0.1^{\text{i}}$	$95.02 \pm 0.0^{\text{g}}$	$92.69 \pm 0.0^{\text{i}}$
	20 mg	$96.3 \pm 0.7^{\text{m}}$	$0.0 \pm 0.0^{\text{a}}$	$2.19 \pm 0.8^{\text{l}}$	$98.49 \pm 0.7^{\text{k,l,j}}$	$97.78 \pm 0.0^{\text{f}}$	$93.79 \pm 0.0^{\text{k}}$
naringenin	5 mg	$82.97 \pm 0.2^{\text{f}}$	$4.15 \pm 0.0^{\text{e}}$	$2.03 \pm 0.1^{\text{k}}$	$89.98 \pm 0.3^{\text{d}}$	$92.21 \pm 0.0^{\text{e}}$	$88.53 \pm 0.0^{\text{d}}$
	10 mg	$80.56 \pm 0.3^{\text{e}}$	$7.47 \pm 0.0^{\text{h}}$	$0.41 \pm 1.1^{\text{b}}$	$93.43 \pm 0.4^{\text{e}}$	$86.23 \pm 0.0^{\text{c}}$	$89.39 \pm 0.0^{\text{e}}$
	20 mg	$78.74 \pm 0.1^{\text{d}}$	$14.09 \pm 0.0^{\text{i}}$	$1.83 \pm 1.0^{\text{j}}$	$94.66 \pm 0.1^{\text{f}}$	$83.18 \pm 0.0^{\text{b}}$	$90.12 \pm 0.0^{\text{f}}$
<i>trans</i> -ferulic acid	5 mg	$94.6 \pm 0.4^{\text{j,k}}$	$1.72 \pm 0.0^{\text{c}}$	$0.21 \pm 1.1^{\text{a}}$	$97.39 \pm 0.4^{\text{ij}}$	$97.13 \pm 0.0^{\text{j,k}}$	$94.06 \pm 0.0^{\text{f}}$
	10 mg	$96.73 \pm 0.0^{\text{m}}$	$0.79 \pm 0.0^{\text{b}}$	$1.17 \pm 0.0^{\text{h}}$	$99.48 \pm 0.0^{\text{m}}$	$97.23 \pm 0.0^{\text{j,k,l}}$	$95.51 \pm 0.0^{\text{o}}$
	20 mg	$89.24 \pm 0.0^{\text{g}}$	$2.37 \pm 0.0^{\text{d}}$	$1.65 \pm 0.0^{\text{i}}$	$93.25 \pm 0.0^{\text{e}}$	$95.69 \pm 0.0^{\text{h}}$	$91.89 \pm 0.0^{\text{g}}$
<i>p</i> -coumaric acid	5 mg	$95.33 \pm 0.0^{\text{l,j}}$	$0.0 \pm 0.0^{\text{a}}$	$0.88 \pm 0.0^{\text{e,f}}$	$96.21 \pm 0.0^{\text{g,h}}$	$99.09 \pm 0.0^{\text{m}}$	$93.94 \pm 0.0^{\text{l}}$
	10 mg	$96.73 \pm 0.0^{\text{m}}$	$2.38 \pm 0.0^{\text{d}}$	$0.87 \pm 0.0^{\text{e,f}}$	$99.98 \pm 0.0^{\text{m}}$	$96.75 \pm 0.0^{\text{ij}}$	$96.18 \pm 0.0^{\text{r}}$
	20 mg	$95.31 \pm 0.0^{\text{l,j}}$	$0.0 \pm 0.0^{\text{a}}$	$0.93 \pm 0.0^{\text{f,g}}$	$96.25 \pm 0.0^{\text{g,h}}$	$99.03 \pm 0.0^{\text{m}}$	$96.65 \pm 0.0^{\text{s}}$
quercetin	5 mg	$94.92 \pm 0.3^{\text{k,l,j}}$	$0.0 \pm 0.0^{\text{a}}$	$3.33 \pm 0.0^{\text{n}}$	$98.24 \pm 0.3^{\text{j,k,l}}$	$96.62 \pm 0.0^{\text{i}}$	$93.41 \pm 0.0^{\text{j}}$
	10 mg	$96.52 \pm 0.1^{\text{m}}$	$0.0 \pm 0.0^{\text{a}}$	$2.7 \pm 0.0^{\text{m}}$	$99.21 \pm 0.1^{\text{l,m}}$	$97.28 \pm 0.0^{\text{k,l,j}}$	$94.36 \pm 0.0^{\text{m}}$
	20 mg	$94.73 \pm 0.0^{\text{j,k,l}}$	$0.0 \pm 0.0^{\text{a}}$	$2.18 \pm 0.0^{\text{l}}$	$96.9 \pm 0.0^{\text{h,i}}$	$97.7 \pm 0.05^{\text{f}}$	$93.41 \pm 0.0^{\text{j}}$
kaempferol	5 mg	$98.7 \pm 0.0^{\text{n}}$	$0.0 \pm 0.0^{\text{a}}$	$1.17 \pm 0.0^{\text{h}}$	$99.88 \pm 0.0^{\text{m}}$	$98.83 \pm 0.0^{\text{m}}$	$95.75 \pm 0.0^{\text{p}}$
	10 mg	$93.37 \pm 0.0^{\text{i}}$	$1.58 \pm 0.0^{\text{c}}$	$0.97 \pm 0.0^{\text{f,g}}$	$97.50 \pm 0.0^{\text{ij}}$	$95.76 \pm 0.0^{\text{h}}$	$94.06 \pm 0.0^{\text{f}}$
	20 mg	$96.16 \pm 0.0^{\text{m}}$	$0.0 \pm 0.0^{\text{a}}$	$1.06 \pm 0.0^{\text{g,h}}$	$99.37 \pm 0.0^{\text{l,m}}$	$96.76 \pm 0.0^{\text{ij}}$	$95.55 \pm 0.0^{\text{o}}$
Wheat starch without the addition of polyphenols		$98.97 \pm 0.0^{\text{n}}$	$0.0 \pm 0.0^{\text{a}}$	$0.78 \pm 0.0^{\text{d,e}}$	$99.75 \pm 0.0^{\text{m}}$	$99.22 \pm 0.0^{\text{m}}$	$94.67 \pm 0.0^{\text{n}}$

The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters in columns differ significantly at $p < 0.05$. * values in bold are the lowest (RDS, TS, SDI, and eGI) or highest (SDS, RS) in columns.

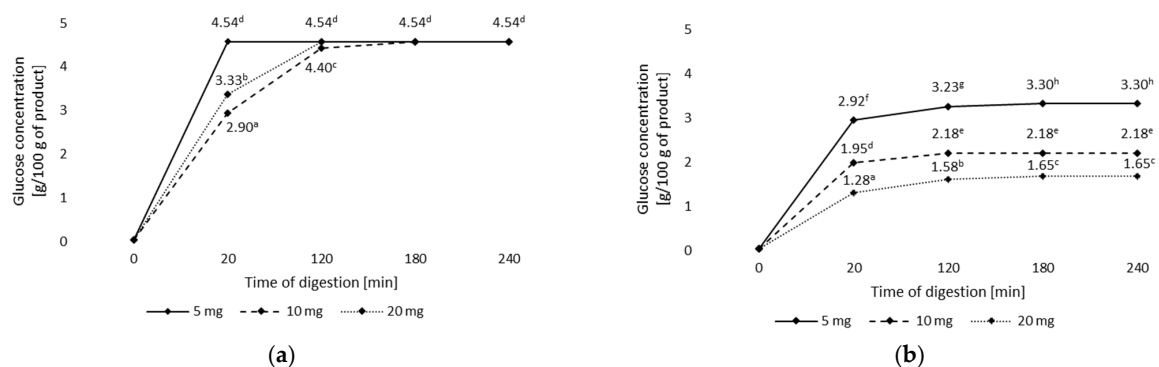


Figure 1. Glucose concentration ($\text{g}/100 \text{ g}$ of product) during the process of wheat starch digestion with the addition of (a) kaempferol (the addition of polyphenol before starch pasting) and (b) epigallocatechin gallate (the addition of polyphenol after starch pasting). The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters differ significantly at $p < 0.05$.

Moreover, in both cases, eGI values were the lowest with the addition of epigallocatechin gallate (20 mg) (50.59, 57.90, respectively, $p < 0.05$, Tables 1 and 2).

3.3. Rice Starch

In the case of rice starch (polyphenol addition prior to starch gelatinization), the lowest values of RDS and SDI were observed when epigallocatechin gallate (10 mg) was added to the starch (16.57 g·100 g⁻¹ d.m. and 31.75 g·100 g⁻¹ d.m., respectively, $p < 0.05$, Table 3). The lowest values of TS and eGI were observed following the addition of epigallocatechin gallate (20 mg) (27.03 g·100 g⁻¹ d.m., 55.16, respectively, $p < 0.05$, Table 3). Concerning SDS, the most effective was trans-ferulic acid (10 mg) (58.23 g·100 g⁻¹ d.m., $p < 0.05$, Table 3, Figure 2a). The highest content of RS was observed in a controlled trial (0.95 g·100 g⁻¹ d.m., $p < 0.05$, Table 3).

Table 3. RDS, SDS, RS, TS, SDI, and eGI values (g·100 g⁻¹ d.m.) in rice starch (polyphenol addition prior to starch gelatinization) depending on the type and dose of the added polyphenol standard.

		RDS	SDS	RS	TS	SDI	eGI
Rice starch with the addition of							
(+)catechin	5 mg	65.56 ± 0.2 ^h	30.49 ± 0.1 ^j	0.0 ± 0.0 ^a	99.11 ± 0.3 ^{j,k}	66.15 ± 0.0 ^f	91.35 ± 0.0 ⁱ
	10 mg	96.51 ± 0.4 ^s	0.85 ± 0.0 ^b	0.0 ± 0.0 ^a	98.21 ± 0.4 ⁱ	98.28 ± 0.0 ^o	96.07 ± 0.0 ^p
	20 mg	92.12 ± 0.3 ^o	1.59 ± 0.0 ^c	0.0 ± 0.0 ^a	93.71 ± 0.3 ^f	98.31 ± 0.0 ^o	93.09 ± 0.0 ^l
epigallocatechin gallate	5 mg	42.58 ± 0.0 ^d	3.15 ± 0.0 ^d	0.48 ± 0.0 ^e	47.79 ± 0.0 ^b	89.09 ± 0.0 ^j	65.56 ± 0.0 ^c
	10 mg	16.57 ± 0.0^{a*}	35.63 ± 0.0 ^k	0.0 ± 0.0 ^a	52.20 ± 0.0 ^c	31.75 ± 0.0^a	64.67 ± 0.0 ^b
	20 mg	27.03 ± 0.0 ^b	0.0 ± 0.0 ^a	0.0 ± 0.0 ^a	27.03 ± 0.0^a	100.0 ± 0.0 ^t	55.16 ± 0.0^a
hesperidin	5 mg	97.37 ± 0.8 ^t	0.0 ± 0.0 ^a	0.49 ± 0.0 ^e	99.45 ± 0.9 ^{k,l}	97.90 ± 0.0 ⁿ	94.69 ± 0.0 ⁿ
	10 mg	58.23 ± 0.0 ^g	40.76 ± 0.0 ^l	0.1 ± 0.0 ^b	99.10 ± 0.0 ^{j,k}	58.76 ± 0.0 ^e	90.54 ± 0.0 ^h
	20 mg	95.67 ± 0.0 ^r	0.0 ± 0.0 ^a	0.2 ± 0.0 ^c	95.87 ± 0.0 ^h	99.80 ± 0.0 ^{s,t}	94.24 ± 0.0 ^m
naringenin	5 mg	70.41 ± 0.2 ^j	22.96 ± 0.1 ^h	0.0 ± 0.0 ^a	93.37 ± 0.3 ^{e,f}	75.41 ± 0.0 ^h	90.05 ± 0.0 ^g
	10 mg	86.44 ± 0.2 ^l	3.39 ± 0.0 ^e	0.0 ± 0.0 ^a	94.91 ± 0.3 ^g	91.07 ± 0.0 ^k	92.08 ± 0.0 ^k
	20 mg	88.44 ± 0.0 ^m	5.63 ± 0.0 ^f	0.0 ± 0.0 ^a	94.06 ± 0.0 ^f	94.02 ± 0.0 ⁱ	93.18 ± 0.0 ^l
trans-ferulic acid	5 mg	91.65 ± 0.0 ^o	0.0 ± 0.0 ^a	0.39 ± 0.0 ^d	92.04 ± 0.0 ^d	99.58 ± 0.0 ^{r,s}	91.65 ± 0.0 ^j
	10 mg	41.60 ± 0.0 ^c	58.23 ± 0.0ⁿ	0.1 ± 0.0 ^b	99.93 ± 0.0 ^l	41.62 ± 0.0 ^b	88.06 ± 0.0 ^d
	20 mg	87.69 ± 0.1 ⁱ	5.63 ± 0.0 ^f	0.39 ± 0.0 ^d	93.71 ± 0.1 ^f	93.57 ± 0.0 ^l	91.71 ± 0.0 ^j
p-coumaric acid	5 mg	92.92 ± 0.6 ^p	0.0 ± 0.0 ^a	0.0 ± 0.0 ^a	92.92 ± 0.6 ^e	100.0 ± 0.0 ^t	93.50 ± 0.0 ⁱ
	10 mg	48.40 ± 0.0 ^e	48.40 ± 0.0 ^m	0.0 ± 0.0 ^a	98.50 ± 0.0 ^{l,j}	49.14 ± 0.0 ^c	88.60 ± 0.0 ^e
	20 mg	97.44 ± 0.0 ^t	0.0 ± 0.0 ^a	0.50 ± 0.0 ^e	99.56 ± 0.0 ^{k,l}	97.87 ± 0.5 ⁿ	95.43 ± 0.0 ^o
quercetin	5 mg	99.27 ± 1.0 ^u	0.0 ± 0.0 ^a	0.78 ± 0.1 ^g	99.76 ± 0.5 ^{k,l}	99.51 ± 0.5 ^r	95.68 ± 0.6 ^o
	10 mg	51.58 ± 0.0 ^f	48.25 ± 0.0 ⁱ	0.0 ± 0.0 ^a	99.83 ± 0.0 ^{k,l}	51.67 ± 0.0 ^d	89.55 ± 0.0 ^f
	20 mg	90.35 ± 0.0 ⁿ	0.0 ± 0.0 ^a	0.58 ± 0.0 ^f	94.10 ± 0.0 ^f	96.01 ± 0.0 ^m	92.23 ± 0.0 ^k
kaempferol	5 mg	66.96 ± 0.7 ⁱ	25.87 ± 0.3 ⁱ	0.0 ± 0.0 ^a	92.83 ± 1.0 ^e	72.13 ± 0.0 ^g	89.59 ± 0.0 ^f
	10 mg	74.21 ± 0.3 ^k	13.49 ± 0.1 ^g	0.0 ± 0.0 ^a	93.61 ± 0.4 ^{e,f}	79.28 ± 0.0 ⁱ	89.96 ± 0.0 ^g
	20 mg	99.19 ± 0.0 ^u	0.0 ± 0.0 ^a	0.0 ± 0.0 ^a	99.19 ± 0.0 ^{j,k,l}	100.0 ± 0.0 ^t	96.74 ± 0.0 ^r
Rice starch without the addition of polyphenols		98.91 ± 0.0 ^u	0.0 ± 0.0 ^a	0.95 ± 0.0^h	99.85 ± 0.0 ^{k,l}	99.05 ± 0.0 ^p	95.64 ± 0.0 ^o

The results are presented as mean ± standard deviation (SD). Values marked with different letters in columns differ significantly at $p < 0.05$. * values in bold are the lowest (RDS, TS, SDI, and eGI) or highest (SDS, RS) in columns.

Regarding the addition of polyphenol after rice starch gelatinization, the lowest values of RDS, TS, and eGI were observed when epigallocatechin gallate (20 mg) was added to the starch (30.86 g·100 g⁻¹ d.m., 33.97 g·100 g⁻¹ d.m., 57.98, respectively, $p < 0.05$, Table 4). In terms of SDS and SDI, the addition of quercetin (10 mg) was the most efficacious (31.89 g·100 g⁻¹ d.m., 60.16 g·100 g⁻¹ d.m., respectively, $p < 0.05$, Table 4, Figure 2b). The highest content of RS was observed when (+)catechin (20 mg) was added to the starch (1.04 g·100 g⁻¹ d.m., $p < 0.05$, Table 4).

Table 4. RDS, SDS, RS, TS, SDI, and eGI values ($\text{g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$) in rice starch (polyphenol addition after starch gelatinization) depending on the type and dose of the added polyphenol standard.

		RDS	SDS	RS	TS	SDI	eGI
Rice starch with the addition of							
(+) catechin	5 mg	95.15 $\pm$ 0.0 ^j	3.17 $\pm$ 0.0 ^e	0.58 $\pm$ 0.0 ^e	98.91 $\pm$ 0.0 ^h	98.19 $\pm$ 0.0 ^h	95.17 $\pm$ 0.0 ^l
	10 mg	98.73 $\pm$ 0.0 ^{l,m}	0.0 $\pm$ 0.0 ^a	0.98 $\pm$ 0.0 ⁱ	99.70 $\pm$ 0.0 ^{j,k}	99.02 $\pm$ 0.0 ^{l,j}	94.88 $\pm$ 0.0 ^k
	20 mg	92.12 $\pm$ 0.0 ⁱ	0.85 $\pm$ 0.0 ^b	1.04 $\pm$ 0.0^j	98.23 $\pm$ 0.0 ^g	93.78 $\pm$ 0.0 ^g	93.62 $\pm$ 0.0 ⁱ
epigallocatechin gallate	5 mg	65.21 $\pm$ 0.4 ^d	1.59 $\pm$ 0.0 ^c	0.20 $\pm$ 0.0 ^b	70.97 $\pm$ 0.4 ^c	91.88 $\pm$ 0.0 ^f	78.46 $\pm$ 0.0 ^c
	10 mg	34.40 $\pm$ 0.2 ^b	10.55 $\pm$ 0.5 ^j	0.0 $\pm$ 0.0 ^a	46.51 $\pm$ 0.2 ^b	73.95 $\pm$ 0.9 ^b	64.02 $\pm$ 0.0 ^b
	20 mg	30.86 $\pm$ 0.0^{a*}	0.83 $\pm$ 0.0 ^b	0.61 $\pm$ 0.0 ^f	33.97 $\pm$ 0.0^a	90.83 $\pm$ 0.0 ^e	57.98 $\pm$ 0.0^a
hesperidin	5 mg	98.81 $\pm$ 0.3 ^{l,m,n}	0.0 $\pm$ 0.0 ^a	0.20 $\pm$ 0.0 ^b	99.01 $\pm$ 0.3 ^{h,i}	99.80 $\pm$ 0.0 ^{j,k,l}	95.69 $\pm$ 0.0 ⁿ
	10 mg	98.97 $\pm$ 0.8 ^{l,m,n}	1.94 $\pm$ 0.5 ^d	0.0 $\pm$ 0.0 ^a	99.74 $\pm$ 0.1 ^{j,k}	99.22 $\pm$ 1.1 ^{l,j,k}	96.79 $\pm$ 0.0 ^w
	20 mg	92.48 $\pm$ 0.1 ⁱ	4.95 $\pm$ 0.0 ^g	0.61 $\pm$ 0.0 ^f	98.04 $\pm$ 0.1 ^g	94.33 $\pm$ 0.0 ^g	94.56 $\pm$ 0.0
naringenin	5 mg	99.10 $\pm$ 0.0 ⁿ	0.0 $\pm$ 0.0 ^a	0.39 $\pm$ 0.0 ^c	99.90 $\pm$ 0.0 ^{j,k}	99.61 $\pm$ 0.0 ^{j,k,l}	96.54 $\pm$ 0.0 ^t
	10 mg	99.30 $\pm$ 0.0 ^{m,n}	0.0 $\pm$ 0.0 ^a	0.77 $\pm$ 0.0 ^g	100.00 $\pm$ 0.0 ^k	99.30 $\pm$ 0.0 ^{l,j,k,l}	96.66 $\pm$ 0.0 ^u
	20 mg	99.43 $\pm$ 0.4 ^{m,n}	0.0 $\pm$ 0.0 ^a	0.0 $\pm$ 0.0 ^a	99.43 $\pm$ 0.4 ^{h,l,j,k}	100.00 $\pm$ 0.0 ^l	96.34 $\pm$ 0.0 ^r
<i>trans</i> -ferulic acid	5 mg	97.51 $\pm$ 0.7 ^k	1.60 $\pm$ 0.0 ^c	0.20 $\pm$ 0.0 ^b	99.31 $\pm$ 0.7 ^{h,l,j}	98.19 $\pm$ 0.0 ^h	95.46 $\pm$ 0.0 ⁱ
	10 mg	82.45 $\pm$ 0.5 ^g	6.25 $\pm$ 0.0 ^h	0.0 $\pm$ 0.0 ^a	94.49 $\pm$ 0.0 ^f	87.25 $\pm$ 0.5 ^d	90.43 $\pm$ 0.0 ^h
	20 mg	87.96 $\pm$ 0.5 ^h	0.0 $\pm$ 0.0 ^a	0.41 $\pm$ 0.0 ^d	89.20 $\pm$ 0.5 ^e	98.61 $\pm$ 0.0 ⁱ	90.01 $\pm$ 0.0 ^g
<i>p</i> -coumaric acid	5 mg	97.93 $\pm$ 0.0 ^{k,l}	1.58 $\pm$ 0.0 ^c	0.39 $\pm$ 0.0 ^c	99.90 $\pm$ 0.0 ^{j,k}	98.03 $\pm$ 0.0 ^h	96.31 $\pm$ 0.0 ^p
	10 mg	77.98 $\pm$ 0.0 ^f	8.04 $\pm$ 0.0 ⁱ	0.0 $\pm$ 0.0 ^a	86.02 $\pm$ 0.0 ^d	90.65 $\pm$ 0.0 ^e	88.33 $\pm$ 0.0 ^e
	20 mg	99.38 $\pm$ 0.4 ^{m,n}	0.0 $\pm$ 0.0 ^a	0.0 $\pm$ 0.0 ^a	99.38 $\pm$ 0.4 ^{h,l,j}	100.00 $\pm$ 0.0 ^l	96.34 $\pm$ 0.0 ^r
quercetin	5 mg	98.51 $\pm$ 0.1 ^{l,j}	0.79 $\pm$ 0.0 ^b	0.19 $\pm$ 0.0 ^b	99.50 $\pm$ 0.1 ^{h,l,j,k}	99.01 $\pm$ 0.0 ^{l,j}	96.36 $\pm$ 0.0 ^s
	10 mg	59.89 $\pm$ 0.2 ^c	31.89 $\pm$ 0.1^k	0.0 $\pm$ 0.0 ^a	99.56 $\pm$ 0.3 ^{l,j,k}	60.16 $\pm$ 0.3^a	88.86 $\pm$ 0.0 ^f
	20 mg	98.85 $\pm$ 0.1 ^{l,m,n}	0.83 $\pm$ 0.5 ^b	0.61 $\pm$ 0.0 ^f	99.46 $\pm$ 0.1 ^{h,l,j,k}	99.39 $\pm$ 0.0 ^{j,k,l}	96.24 $\pm$ 0.0 ^o
kaempferol	5 mg	97.84 $\pm$ 0.1 ^k	0.0 $\pm$ 0.0 ^a	0.39 $\pm$ 0.0 ^c	98.22 $\pm$ 0.1 ^g	99.61 $\pm$ 0.0 ^{j,k,l}	95.64 $\pm$ 0.0 ^m
	10 mg	99.50 $\pm$ 0.0 ⁿ	0.0 $\pm$ 0.0 ^a	0.77 $\pm$ 0.0 ^g	100.00 $\pm$ 0.0 ^k	99.50 $\pm$ 0.0 ^{j,k,l}	96.66 $\pm$ 0.0 ^u
	20 mg	71.84 $\pm$ 0.0 ^e	4.04 $\pm$ 0.0 ^f	0.0 $\pm$ 0.0 ^a	85.56 $\pm$ 0.0 ^d	83.96 $\pm$ 0.0 ^c	84.76 $\pm$ 0.0 ^d
Rice starch without the addition of polyphenols		98.91 $\pm$ 0.0 ^{l,m,n}	0.0 $\pm$ 0.0 ^a	0.95 $\pm$ 0.0 ^h	99.85 $\pm$ 0.0 ^{j,k}	99.05 $\pm$ 0.0 ^{l,j}	95.64 $\pm$ 0.0 ^m

The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters in columns differ significantly at $p < 0.05$. * values in bold are the lowest (RDS, TS, SDI, and eGI) or highest (SDS, RS) in columns.

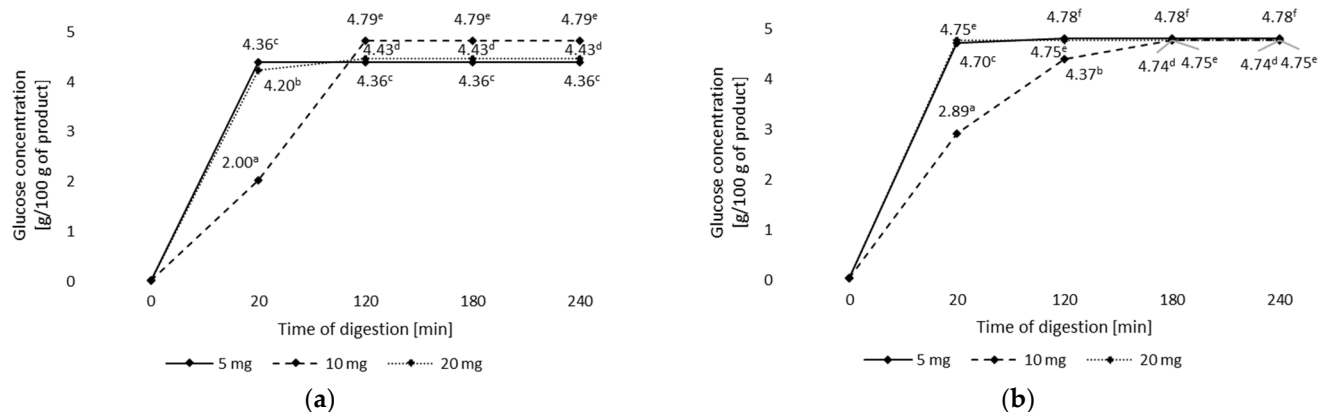


Figure 2. Glucose concentration ($\text{g}/100 \text{ g}$ of product) during the process of wheat starch digestion with the addition of (a) *trans*-ferulic acid (the addition of polyphenol before starch pasting) and (b) quercetin (the addition of polyphenol after starch pasting). The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters differ significantly at $p < 0.05$.

3.4. Potato Starch

In the case of potato starch (polyphenol addition prior to starch gelatinization), the lowest values of RDS, TS, and eGI were obtained when epigallocatechin gallate (20 mg) was added to the starch (16.93 g·100 g⁻¹ d.m., 17.78 g·100 g⁻¹ d.m., 49.46, respectively, $p < 0.05$, Table 5). Epigallocatechin gallate (10 mg) exhibited the lowest value of SDI (41.41 g·100 g⁻¹ d.m., $p < 0.05$, Table 5). The highest value of SDS was observed when quercetin (20 mg) was added to the starch (48.77 g·100 g⁻¹ d.m., $p < 0.05$, Table 5, Figure 3a). The highest value of RS was observed with the addition of hesperidin (5 mg) (2.15 g·100 g⁻¹ d.m., $p < 0.05$, Table 5).

Table 5. RDS, SDS, RS, TS, SDI, and eGI values (g·100 g⁻¹ d.m.) in potato starch (polyphenol addition prior to starch gelatinization) depending on the type and dose of the added polyphenol standard.

		RDS	SDS	RS	TS	SDI	eGI
Potato starch with the addition of							
(+)catechin	5 mg	90.85 ± 0.0 ^j	4.02 ± 0.0 ^e	0.0 ± 0.0 ^a	97.28 ± 0.0 ^g	93.39 ± 0.0 ⁱ	94.38 ± 0.0 ^l
	10 mg	96.22 ± 1.2 [†]	0.0 ± 0.0 ^a	0.84 ± 0.0 ^g	98.59 ± 1.2 ⁱ	97.60 ± 0.0 ^{l,†}	95.06 ± 0.0 ^p
	20 mg	91.09 ± 0.0 ^j	0.0 ± 0.0 ^a	1.86 ± 0.0 ^l	93.71 ± 0.0 ^e	97.20 ± 0.0 ^l	93.25 ± 0.0 ^j
epigallocatechin gallate	5 mg	44.53 ± 0.2 ^c	15.90 ± 0.1 ⁱ	0.54 ± 0.1 ^d	60.96 ± 0.4 ^c	73.04 ± 0.1 ^d	72.18 ± 0.0 ^c
	10 mg	21.17 ± 0.6 ^b	29.16 ± 0.6 ^j	0.0 ± 0.0 ^a	51.12 ± 0.0 ^b	41.41 ± 1.1^a	64.87 ± 0.0 ^b
	20 mg	16.93 ± 0.0^{a*}	0.0 ± 0.0 ^a	0.85 ± 0.0 ^g	17.78 ± 0.0^a	95.22 ± 0.0 ^j	49.46 ± 0.0^a
hesperidin	5 mg	97.07 ± 0.3 ^m	0.38 ± 0.5 ^a	2.15 ± 0.0[†]	99.60 ± 0.8 ^j	97.46 ± 0.5 ^{l,†}	95.59 ± 0.0 ^s
	10 mg	95.86 ± 0.0 [†]	1.60 ± 0.0 ^b	0.0 ± 0.0 ^a	97.45 ± 0.0 ^{g,h}	98.36 ± 0.0 ^{m,n}	96.23 ± 0.0 ^w
	20 mg	64.29 ± 0.0 ^e	32.89 ± 0.5 ^k	1.18 ± 0.0 ⁱ	98.73 ± 0.0 ⁱ	65.12 ± 0.0 ^c	91.22 ± 0.0 ^g
naringenin	5 mg	84.95 ± 0.0 ^h	12.02 ± 0.0 ^h	0.20 ± 0.0 ^b	97.16 ± 0.0 ^g	87.43 ± 0.0 ^g	93.76 ± 0.0 ^k
	10 mg	96.12 ± 0.0 [†]	0.0 ± 0.0 ^a	0.74 ± 0.0 ^f	97.61 ± 0.0 ^{g,h}	98.48 ± 0.0 ^{m,n}	95.93 ± 0.0 ^t
	20 mg	95.85 ± 1.0 [†]	2.26 ± 0.0 ^c	0.56 ± 0.0 ^d	98.67 ± 1.1 ⁱ	97.14 ± 0.0 ^l	97.10 ± 0.0 ^y
trans-ferulic acid	5 mg	94.42 ± 0.0 ^k	3.02 ± 0.0 ^d	0.93 ± 0.0 ^h	98.37 ± 0.0 ^{h,i}	95.99 ± 0.0 ^k	96.00 ± 0.0 ^u
	10 mg	90.71 ± 0.0 ^j	3.18 ± 0.0 ^d	0.0 ± 0.0 ^a	95.49 ± 0.0 ^f	95.00 ± 0.0 ^j	94.49 ± 0.0 [†]
	20 mg	79.81 ± 0.0 ^g	11.82 ± 0.0 ^h	1.45 ± 0.0 ^k	93.09 ± 0.0 ^e	85.74 ± 0.0 ^f	90.92 ± 0.0 ^f
p-coumaric acid	5 mg	89.58 ± 0.0 ⁱ	0.0 ± 0.0 ^a	0.29 ± 0.0 ^c	91.44 ± 0.0 ^d	97.97 ± 0.0 ^{l,m}	92.36 ± 0.0 ^h
	10 mg	98.48 ± 0.3 ⁿ	1.59 ± 0.0 ^b	0.0 ± 0.0 ^a	99.94 ± 0.1 ^j	98.54 ± 0.2 ⁿ	98.09 ± 0.0 ^z
	20 mg	94.86 ± 0.8 ^{k,l}	0.0 ± 0.0 ^a	0.84 ± 0.0 ^g	95.71 ± 0.8 ^f	99.12 ± 0.0 ^o	94.68 ± 0.0 ⁿ
quercetin	5 mg	76.25 ± 0.1 ^f	11.13 ± 0.0 ^g	1.36 ± 0.0 ^j	92.01 ± 0.0 ^d	82.88 ± 0.1 ^e	89.21 ± 0.0 ^e
	10 mg	89.37 ± 0.0 ⁱ	7.97 ± 0.0 ^f	0.0 ± 0.0 ^a	97.27 ± 0.0 ^g	91.88 ± 0.0 ^h	95.26 ± 0.0 ^r
	20 mg	45.82 ± 0.0 ^d	48.77 ± 0.0^l	0.63 ± 0.0 ^e	95.23 ± 0.0 ^f	48.11 ± 0.0 ^b	87.05 ± 0.0 ^d
kaempferol	5 mg	89.40 ± 0.0 ⁱ	1.60 ± 0.0 ^b	0.20 ± 0.0 ^b	97.58 ± 0.0 ^{g,h}	91.62 ± 0.0 ^h	93.20 ± 0.0 ⁱ
	10 mg	95.35 ± 0.0 ^{l,†}	0.0 ± 0.0 ^a	0.93 ± 0.0 ^h	100.00 ± 0.0 ^j	95.35 ± 0.0 ^j	94.87 ± 0.0 ^o
	20 mg	97.26 ± 0.1 ^m	1.52 ± 0.0 ^b	0.65 ± 0.0 ^e	98.67 ± 0.1 ⁱ	98.57 ± 0.0 ⁿ	97.10 ± 0.0 ^y
Potato starch without the addition of polyphenols		91.39 ± 0.0 ^j	2.45 ± 0.0 ^c	0.0 ± 0.0 ^a	97.62 ± 0.0 ^{g,h,i}	93.33 ± 0.0 ⁱ	94.55 ± 0.0 ^m

The results are presented as mean ± standard deviation (SD). Values marked with different letters in columns differ significantly at $p < 0.05$. * values in bold are the lowest (RDS, TS, SDI, and eGI) or highest (SDS, RS) in columns.

Considering the addition of polyphenol after potato starch gelatinization, epigallocatechin gallate (5 mg) contributed to the lowest value of TS, 10 mg—RS, and 20 mg—RDS and eGI (24.13 g·100 g⁻¹ d.m., 5.46 g·100 g⁻¹ d.m., 16.41 g·100 g⁻¹ d.m., 52.65, respectively, $p < 0.05$, Table 6). In terms of SDS, the highest values were obtained when naringenin (10 mg) and kaempferol (10 mg) were added to the starch (66.70 g·100 g⁻¹ d.m., 66.19 g·100 g⁻¹ d.m., respectively, $p < 0.05$, Table 6, Figure 3b). The most efficient polyphenol in the case of SDI was naringenin (10 mg) (27.78 g·100 g⁻¹ d.m., $p < 0.05$, Table 6).

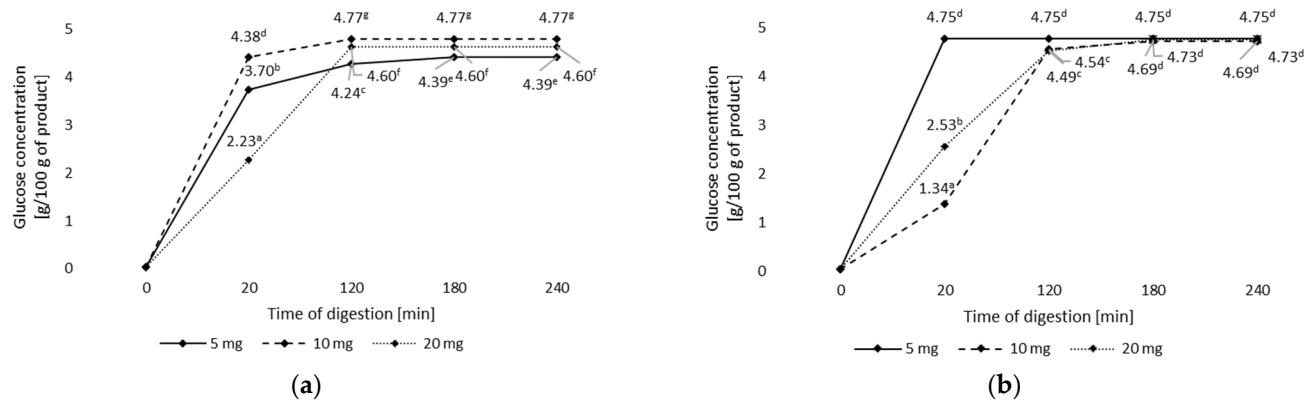


Figure 3. Glucose concentration (g/100 g of product) during the process of wheat starch digestion with the addition of (a) quercetin (the addition of polyphenol before starch pasting) and (b) naringenin (the addition of polyphenol after starch pasting). The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters differ significantly at $p < 0.05$.

Table 6. RDS, SDS, RS, TS, SDI, and eGI values ($\text{g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$) in potato starch (polyphenol addition after starch gelatinization) depending on the type and dose of the added polyphenol standard.

		RDS	SDS	RS	TS	SDI	eGI
Potato starch with the addition of							
(+)catechin	5 mg	96.27 $\pm$ 0.3 ^y	2.51 $\pm$ 0.0 ^b	0.82 $\pm$ 0.0 ^b	99.60 $\pm$ 0.3 ^{l,m}	98.65 $\pm$ 0.0 ^u	96.93 $\pm$ 0.0 ^p
	10 mg	39.18 $\pm$ 0.0 ^g	56.08 $\pm$ 0.0 ⁿ	0.0 $\pm$ 0.0 ^a	99.86 $\pm$ 0.0 ^m	39.23 $\pm$ 0.0 ^d	87.39 $\pm$ 0.0 ^{h,i}
	20 mg	57.85 $\pm$ 0.2 ^m	38.57 $\pm$ 0.1 ^h	0.0 $\pm$ 0.0 ^a	96.42 $\pm$ 0.3 ^g	60.00 $\pm$ 0.0 ^l	89.56 $\pm$ 0.0 ^l
epigallocatechin gallate	5 mg	44.76 $\pm$ 0.3 ⁱ	15.99 $\pm$ 0.1 ^f	0.10 $\pm$ 0.1 ^a	24.13 $\pm$ 0.5 ^a	69.89 $\pm$ 0.2 ^m	72.86 $\pm$ 0.0 ^c
	10 mg	22.66 $\pm$ 0.1 ^b	14.84 $\pm$ 0.1 ^e	5.46 $\pm$ 0.0 ^g	49.99 $\pm$ 0.2 ^b	45.32 $\pm$ 0.0 ^f	61.11 $\pm$ 0.0 ^b
	20 mg	16.41 $\pm$ 0.1 ^{a*}	6.76 $\pm$ 0.0 ^c	0.0 $\pm$ 0.0 ^a	64.04 $\pm$ 0.1 ^c	68.00 $\pm$ 0.0 ^l	52.65 $\pm$ 0.0 ^a
hesperidin	5 mg	76.50 $\pm$ 0.1 ^r	15.94 $\pm$ 0.0 ^f	1.17 $\pm$ 0.0 ^c	94.41 $\pm$ 0.1 ^{d,e}	81.03 $\pm$ 0.0 ^o	90.78 $\pm$ 0.0 ^m
	10 mg	43.97 $\pm$ 0.2 ^h	20.81 $\pm$ 1.8 ^g	1.16 $\pm$ 0.0 ^c	98.51 $\pm$ 0.5 ^{k,l}	44.63 $\pm$ 0.0 ^e	81.40 $\pm$ 0.2 ^d
	20 mg	38.34 $\pm$ 0.0 ^f	58.35 $\pm$ 0.0 ^o	0.0 $\pm$ 0.0 ^a	96.69 $\pm$ 0.0 ^{g,h}	39.66 $\pm$ 0.0 ^d	86.16 $\pm$ 0.0 ^f
naringenin	5 mg	98.16 $\pm$ 0.1 ^z	0.0 $\pm$ 0.0 ^a	0.83 $\pm$ 0.0 ^b	98.99 $\pm$ 0.1 ^{l,l}	99.16 $\pm$ 0.0 ^w	96.21 $\pm$ 0.0 ^p
	10 mg	26.83 $\pm$ 0.1 ^c	66.70 $\pm$ 0.4 ^r	0.0 $\pm$ 0.0 ^a	96.60 $\pm$ 0.5 ^{g,h}	27.78 $\pm$ 0.0 ^a	84.54 $\pm$ 0.0 ^e
	20 mg	50.95 $\pm$ 0.1 ^k	40.38 $\pm$ 0.1 ^l	0.0 $\pm$ 0.0 ^a	96.61 $\pm$ 0.5 ^{g,h}	52.74 $\pm$ 0.2 ⁱ	89.03 $\pm$ 1.0 ^{k,l}
trans-ferulic acid	5 mg	67.40 $\pm$ 0.4 ⁿ	24.87 $\pm$ 0.1 ⁱ	1.62 $\pm$ 0.1 ^d	93.90 $\pm$ 0.5 ^d	71.79 $\pm$ 0.8 ⁿ	88.65 $\pm$ 0.5 ^{j,k}
	10 mg	80.08 $\pm$ 0.0 ^s	15.70 $\pm$ 0.0 ^{e,f}	1.64 $\pm$ 0.0 ^d	97.42 $\pm$ 0.0 ^{l,j}	82.20 $\pm$ 0.0 ^p	92.58 $\pm$ 0.0 ⁿ
	20 mg	90.50 $\pm$ 0.1 ^u	0.0 $\pm$ 0.0 ^a	0.82 $\pm$ 0.0 ^b	98.02 $\pm$ 0.1 ^{j,k}	92.32 $\pm$ 0.0 ^s	93.84 $\pm$ 0.0 ^o
p-coumaric acid	5 mg	81.74 $\pm$ 0.6 ^t	12.28 $\pm$ 0.6 ^j	0.83 $\pm$ 0.0 ^b	95.70 $\pm$ 0.0 ^j	85.41 $\pm$ 0.6 ^r	93.65 $\pm$ 1.6 ^o
	10 mg	43.62 $\pm$ 0.0 ^h	51.27 $\pm$ 0.0 ^m	0.0 $\pm$ 0.0 ^a	94.88 $\pm$ 0.0 ^e	45.97 $\pm$ 0.0 ^g	87.04 $\pm$ 0.0 ^{g,h}
	20 mg	48.16 $\pm$ 0.1 ⁱ	46.23 $\pm$ 0.1 ^l	0.0 $\pm$ 0.0 ^a	98.25 $\pm$ 0.1 ^k	49.02 $\pm$ 0.0 ^h	88.15 $\pm$ 0.0 ^{l,j}
quercetin	5 mg	68.92 $\pm$ 0.0 ^p	23.84 $\pm$ 0.0 ^h	2.14 $\pm$ 0.0 ^e	99.09 $\pm$ 0.6 ^{h,i}	72.02 $\pm$ 0.4 ⁿ	90.50 $\pm$ 0.0 ^{l,m}
	10 mg	51.57 $\pm$ 0.4 ^l	39.07 $\pm$ 0.3 ^k	2.68 $\pm$ 0.5 ^f	99.56 $\pm$ 0.1 ^{l,m}	51.79 $\pm$ 0.3 ⁱ	87.78 $\pm$ 0.0 ^{h,i}
	20 mg	35.01 $\pm$ 0.0 ^e	63.35 $\pm$ 0.0 ^p	0.72 $\pm$ 0.0 ^b	99.08 $\pm$ 0.0 ^{l,l}	35.34 $\pm$ 0.0 ^c	86.36 $\pm$ 0.0 ^{f,g}
kaempferol	5 mg	69.32 $\pm$ 0.0 ^o	26.73 $\pm$ 0.0 ^h	0.20 $\pm$ 0.0 ^a	96.26 $\pm$ 0.0 ^{f,g}	72.02 $\pm$ 0.0 ⁿ	90.81 $\pm$ 0.0 ^m
	10 mg	29.25 $\pm$ 0.1 ^d	66.19 $\pm$ 0.2 ^r	0.0 $\pm$ 0.0 ^a	99.29 $\pm$ 0.3 ^{l,l}	29.46 $\pm$ 0.0 ^b	85.77 $\pm$ 0.0 ^f
	20 mg	55.01 $\pm$ 0.1 ^l	40.53 $\pm$ 0.1 ^l	0.0 $\pm$ 0.0 ^a	98.44 $\pm$ 0.1 ^{k,l}	55.88 $\pm$ 0.0 ^k	89.70 $\pm$ 0.0 ^{l,l}
Potato starch without the addition of polyphenols		91.39 $\pm$ 0.0 ^w	2.45 $\pm$ 0.0 ^b	0.0 $\pm$ 0.0 ^a	97.92 $\pm$ 0.0 ^{j,k}	93.33 $\pm$ 0.0 ^t	94.49 $\pm$ 0.0 ^o

The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters in columns differ significantly at $p < 0.05$. * values in bold are the lowest (RDS, TS, SDI, and eGI) or highest (SDS, RS) in columns.

3.5. Maize Starch

In the case of maize starch (polyphenol addition prior to starch gelatinization), epigallocatechin gallate (5 mg) was the most effective in terms of RDS, SDS, and SDI ($41.78 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $16.20 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $64.27 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, respectively, $p < 0.05$, Table 7, Figure 4a). In terms of TS and eGI, the most effective was epigallocatechin gallate (20 mg) ($46.72 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, 65.47 , respectively, $p < 0.05$, Table 7). The highest value of RS was observed when naringenin (20 mg) was added to the starch ($3.29 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $p < 0.05$, Table 7).

Table 7. RDS, SDS, RS, TS, SDI, and eGI values ($\text{g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$) in maize starch (polyphenol addition prior to starch gelatinization) depending on the type and dose of the added polyphenol standard.

		RDS	SDS	RS	TS	SDI	eGI
Maize starch with the addition of							
(+)catechin	5 mg	83.27 ± 0.0^f	$12.88 \pm 0.0^{\dagger}$	0.21 ± 0.0^b	96.36 ± 0.0^h	86.42 ± 0.0^b	92.96 ± 0.0^f
	10 mg	93.48 ± 0.0^k	3.07 ± 0.0^f	2.26 ± 0.0^r	$98.81 \pm 0.0^{\dagger,m}$	94.62 ± 0.0^i	94.50 ± 0.0^k
	20 mg	97.20 ± 0.0^p	0.0 ± 0.0^a	1.14 ± 0.0^i	98.34 ± 0.0^l	$98.85 \pm 0.0^{o,p}$	95.66 ± 0.0^o
epigallocatechin gallate	5 mg	$41.78 \pm 0.2^{a*}$	16.20 ± 0.1^m	0.21 ± 0.0^b	65.01 ± 0.3^c	64.27 ± 0.0^a	72.36 ± 0.0^c
	10 mg	51.75 ± 0.1^c	2.39 ± 0.0^e	0.88 ± 0.0^g	58.21 ± 0.1^b	88.91 ± 0.0^d	71.03 ± 0.0^b
	20 mg	45.01 ± 0.0^b	0.0 ± 0.0^a	$1.71 \pm 0.0^{\dagger}$	46.72 ± 0.0^a	96.33 ± 0.0^j	65.47 ± 0.0^a
hesperidin	5 mg	81.93 ± 0.0^e	7.68 ± 0.0^i	0.63 ± 0.0^e	90.24 ± 0.0^e	90.79 ± 0.0^f	90.53 ± 0.0^e
	10 mg	$95.59 \pm 0.0^{\dagger}$	0.0 ± 0.0^a	1.88 ± 0.0^n	97.47 ± 0.0^j	$98.08 \pm 0.0^{m,n}$	$94.96 \pm 0.0^{\dagger}$
	20 mg	97.97 ± 0.0^s	0.0 ± 0.0^a	0.86 ± 0.0^f	$98.83 \pm 0.0^{\dagger,m}$	99.13 ± 0.0^p	95.66 ± 0.0^o
naringenin	5 mg	96.17 ± 0.0^m	0.0 ± 0.0^a	2.25 ± 0.0^p	98.42 ± 0.0^l	$97.72 \pm 0.0^{l,\dagger}$	$94.96 \pm 0.0^{\dagger}$
	10 mg	89.44 ± 0.1^h	8.71 ± 0.0^k	0.29 ± 0.0^c	98.43 ± 0.1^l	90.86 ± 0.0^f	94.77 ± 0.0^l
	20 mg	$96.26 \pm 0.1^{m,n}$	0.0 ± 0.0^a	3.29 ± 0.0^w	$99.55 \pm 0.1^{o,p}$	96.70 ± 0.0^k	95.00 ± 0.0^n
trans-ferulic acid	5 mg	97.57 ± 0.4^r	0.83 ± 0.0^b	1.33 ± 0.0^k	$99.74 \pm 0.4^{p,r}$	$97.83 \pm 0.8^{\dagger,m}$	95.90 ± 0.0^p
	10 mg	90.06 ± 0.3^i	2.29 ± 0.0^d	1.97 ± 0.0^o	95.85 ± 0.3^g	93.97 ± 0.0^h	93.09 ± 0.0^g
	20 mg	97.97 ± 0.0^s	0.0 ± 0.0^a	0.57 ± 0.0^d	$98.83 \pm 0.0^{\dagger,m}$	99.13 ± 0.0^p	95.66 ± 0.0^o
p-coumaric acid	5 mg	97.59 ± 0.0^r	0.0 ± 0.0^a	0.95 ± 0.0^h	$98.54 \pm 0.0^{l,\dagger}$	99.04 ± 0.0^p	95.66 ± 0.0^o
	10 mg	97.66 ± 0.3^r	0.0 ± 0.0^a	1.74 ± 0.0^m	$99.40 \pm 0.3^{n,o}$	98.25 ± 0.0^n	95.95 ± 0.0^r
	20 mg	$96.54 \pm 0.3^{n,o}$	0.0 ± 0.0^a	2.52 ± 0.0^t	$99.07 \pm 0.3^{m,n}$	97.45 ± 0.0^l	95.00 ± 0.0^n
quercetin	5 mg	75.55 ± 0.2^d	11.16 ± 0.0^l	0.21 ± 0.0^b	86.92 ± 0.2^d	86.92 ± 0.0^c	88.05 ± 0.0^d
	10 mg	93.86 ± 0.0^l	0.0 ± 0.0^a	1.27 ± 0.0^j	95.13 ± 0.0^f	98.67 ± 0.0^o	93.23 ± 0.0^h
	20 mg	88.64 ± 0.0^g	7.78 ± 0.0^j	2.67 ± 0.0^u	$99.09 \pm 0.0^{m,n}$	89.46 ± 0.0^e	93.62 ± 0.0^j
kaempferol	5 mg	$95.59 \pm 0.0^{\dagger}$	0.0 ± 0.0^a	2.34 ± 0.0^s	97.94 ± 0.0^k	$97.61 \pm 0.0^{l,\dagger}$	$94.96 \pm 0.0^{\dagger}$
	10 mg	90.23 ± 0.1^i	3.17 ± 0.0^g	0.29 ± 0.0^c	96.85 ± 0.1^i	93.16 ± 0.0^g	93.47 ± 0.0^i
	20 mg	93.12 ± 0.0^j	4.66 ± 0.0^h	1.52 ± 0.0^l	$99.30 \pm 0.0^{n,o}$	93.78 ± 0.0^h	94.97 ± 0.0^m
Maize starch without the addition of polyphenols		97.67 ± 0.0^o	1.64 ± 0.0^c	0.0 ± 0.0^a	99.94 ± 0.0^r	96.72 ± 0.0^k	96.31 ± 0.0^s

The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters in columns differ significantly at $p < 0.05$. * values in bold are the lowest (RDS, TS, SDI, and eGI) or highest (SDS, RS) in columns.

In terms of polyphenol addition to maize starch after its gelatinization, the most effective was epigallocatechin gallate (20 mg). The addition resulted in the lowest RDS, TS, SDI, and eGI values ($12.08 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $15.80 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $76.48 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, and 48.13 , respectively; $p < 0.05$; Table 8). The highest value of SDS was observed with the addition of trans-ferulic acid (10 mg) ($8.22 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $p < 0.05$, Table 8, Figure 4b). The highest value of RS was observed with the addition of quercetin (20 mg) ($3.85 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $p < 0.05$, Table 8).

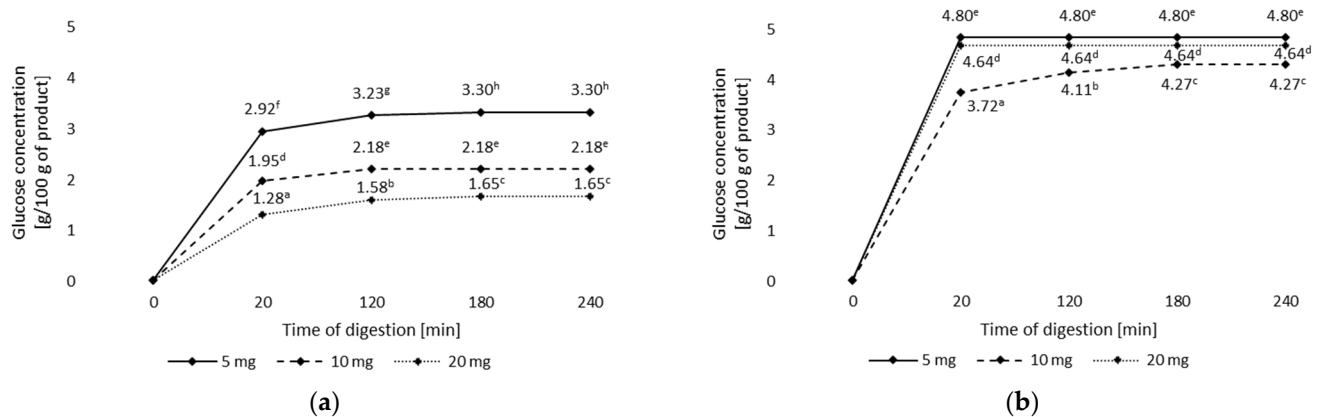


Figure 4. Glucose concentration (g/100 g of product) during the process of wheat starch digestion with the addition of (a) epigallocatechin gallate (the addition of polyphenol before starch pasting) and (b) *trans*-ferulic acid (the addition of polyphenol after starch pasting). The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters differ significantly at $p < 0.05$.

Table 8. RDS, SDS, RS, TS, SDI, and eGI values ($\text{g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$) in maize starch (polyphenol addition after starch gelatinization) depending on the type and dose of the added polyphenol standard.

		RDS	SDS	RS	TS	SDI	eGI
Maize starch with the addition of							
(+)catechin	5 mg	96.52 $\pm$ 0.0 ^{n,o}	0.0 $\pm$ 0.0 ^a	1.38 $\pm$ 0.0 ⁱ	99.51 $\pm$ 0.0 ^m	97.00 $\pm$ 0.0 ^{k,l}	96.34 $\pm$ 0.0 ^m
	10 mg	91.29 $\pm$ 0.0 ^j	7.41 $\pm$ 0.0 ^k	0.0 $\pm$ 0.0 ^a	98.69 $\pm$ 0.0 ^{l,j}	92.50 $\pm$ 0.0 ^d	95.20 $\pm$ 0.0 ^l
	20 mg	95.24 $\pm$ 0.1 ⁱ	0.0 $\pm$ 0.0 ^a	3.17 $\pm$ 0.0 ⁿ	98.41 $\pm$ 0.1 ^l	96.78 $\pm$ 0.0 ^{j,k}	94.19 $\pm$ 0.0 ^j
epigallocatechin gallate	5 mg	52.13 $\pm$ 0.1 ^c	6.42 $\pm$ 0.0 ⁱ	1.18 $\pm$ 0.0 ^h	59.73 $\pm$ 0.1 ^c	87.28 $\pm$ 0.0 ^c	72.70 $\pm$ 0.0 ^c
	10 mg	43.18 $\pm$ 0.0 ^b	0.59 $\pm$ 0.0 ^b	0.0 $\pm$ 0.0 ^a	43.77 $\pm$ 0.0 ^b	98.66 $\pm$ 0.0 ⁿ	64.48 $\pm$ 0.0 ^b
	20 mg	12.08 $\pm$ 0.0 ^{a*}	2.42 $\pm$ 0.0 ^g	0.49 $\pm$ 0.0 ^b	15.80 $\pm$ 0.0 ^a	76.48 $\pm$ 0.0 ^a	48.13 $\pm$ 0.0 ^a
hesperidin	5 mg	99.49 $\pm$ 0.0 ^s	0.0 $\pm$ 0.0 ^a	1.40 $\pm$ 0.0 ^j	100.00 $\pm$ 0.0 ^P	99.49 $\pm$ 0.0 ^r	96.91 $\pm$ 0.0 ⁿ
	10 mg	90.47 $\pm$ 0.0 ⁱ	6.58 $\pm$ 0.0 ^j	0.0 $\pm$ 0.0 ^a	97.87 $\pm$ 0.0 ^k	92.44 $\pm$ 0.0 ^d	94.63 $\pm$ 0.0 ^k
	20 mg	96.16 $\pm$ 0.0 ⁿ	0.0 $\pm$ 0.0 ^a	3.38 $\pm$ 0.0 ^o	99.55 $\pm$ 0.0 ^{m,n}	96.60 $\pm$ 0.0 ^j	95.00 $\pm$ 0.0 ^{k,l}
naringenin	5 mg	98.34 $\pm$ 0.1 ^r	0.0 $\pm$ 0.0 ^a	1.91 $\pm$ 0.0 ^l	100.00 $\pm$ 0.0 ^P	98.34 $\pm$ 0.1 ^m	95.97 $\pm$ 0.0 ^{t,m}
	10 mg	93.26 $\pm$ 0.0 ^l	0.0 $\pm$ 0.0 ^a	0.89 $\pm$ 0.0 ^e	94.15 $\pm$ 0.0 ^h	99.06 $\pm$ 0.0 ^{o,p}	93.22 $\pm$ 0.0 ^h
	20 mg	97.76 $\pm$ 0.5 ^P	0.0 $\pm$ 0.0 ^a	2.08 $\pm$ 0.0 ^t	99.84 $\pm$ 0.6 ^{n,o}	97.92 $\pm$ 0.0 ^t	96.04 $\pm$ 0.0 ^{t,m}
<i>trans</i> -ferulic acid	5 mg	99.46 $\pm$ 0.6 ^s	0.0 $\pm$ 0.0 ^a	1.51 $\pm$ 0.0 ^k	100.00 $\pm$ 0.0 ^P	99.46 $\pm$ 0.6 ^r	96.91 $\pm$ 0.0 ⁿ
	10 mg	76.49 $\pm$ 0.0 ^d	8.22 $\pm$ 0.0 ^l	0.0 $\pm$ 0.0 ^a	88.00 $\pm$ 0.0 ^e	86.92 $\pm$ 0.0 ^b	88.17 $\pm$ 0.0 ^d
	20 mg	96.54 $\pm$ 0.0 ^{n,o}	0.0 $\pm$ 0.0 ^a	3.40 $\pm$ 0.0 ^P	99.94 $\pm$ 0.0 ^o	96.60 $\pm$ 0.0 ^j	95.00 $\pm$ 0.0 ^{k,l}
<i>p</i> -coumaric acid	5 mg	92.94 $\pm$ 0.0 ^l	0.0 $\pm$ 0.0 ^a	0.98 $\pm$ 0.0 ^f	93.92 $\pm$ 0.0 ^{g,h}	98.95 $\pm$ 0.0 ^o	92.92 $\pm$ 0.0 ^h
	10 mg	89.73 $\pm$ 0.0 ^h	0.0 $\pm$ 0.0 ^a	0.79 $\pm$ 0.0 ^d	95.33 $\pm$ 0.0 ⁱ	94.13 $\pm$ 0.0 ^g	91.52 $\pm$ 0.9 ^g
	20 mg	92.54 $\pm$ 0.3 ^k	0.80 $\pm$ 0.0 ^c	2.96 $\pm$ 0.0 ^m	97.92 $\pm$ 0.3 ^k	94.51 $\pm$ 0.0 ^h	93.63 $\pm$ 0.0 ⁱ
quercetin	5 mg	84.76 $\pm$ 0.0 ^e	1.60 $\pm$ 0.0 ^e	0.98 $\pm$ 0.0 ^f	87.34 $\pm$ 0.0 ^d	97.05 $\pm$ 0.0 ^l	89.01 $\pm$ 0.0 ^e
	10 mg	88.00 $\pm$ 0.0 ^g	0.82 $\pm$ 0.0 ^d	0.0 $\pm$ 0.0 ^a	93.76 $\pm$ 0.0 ^g	93.86 $\pm$ 0.0 ^f	91.64 $\pm$ 0.0 ^g
	20 mg	95.79 $\pm$ 0.0 ^m	0.0 $\pm$ 0.0 ^a	3.85 $\pm$ 0.0 ^r	99.64 $\pm$ 0.0 ^{m,n}	96.14 $\pm$ 0.0 ⁱ	95.00 $\pm$ 0.0 ^{k,l}
kaempferol	5 mg	95.72 $\pm$ 0.0 ^m	0.0 $\pm$ 0.0 ^a	0.68 $\pm$ 0.0 ^c	96.40 $\pm$ 0.0 ^j	99.29 $\pm$ 0.0 ^{p,r}	95.07 $\pm$ 0.0 ^l
	10 mg	85.54 $\pm$ 0.0 ^f	4.93 $\pm$ 0.0 ^h	0.0 $\pm$ 0.0 ^a	92.12 $\pm$ 0.0 ^f	92.86 $\pm$ 0.0 ^e	91.11 $\pm$ 0.0 ^f
	20 mg	97.78 $\pm$ 0.3 ^P	0.0 $\pm$ 0.0 ^a	1.05 $\pm$ 0.0 ^g	98.83 $\pm$ 0.3 ^t	98.94 $\pm$ 0.0 ^o	95.66 $\pm$ 0.0 ^t
Maize starch without the addition of polyphenols		96.67 $\pm$ 0.0 ^o	1.64 $\pm$ 0.0 ^f	0.0 $\pm$ 0.0 ^a	99.94 $\pm$ 0.0 ^o	96.72 $\pm$ 0.0 ^j	96.31 $\pm$ 0.0 ^m

The results are presented as mean $\pm$ standard deviation (SD). Values marked with different letters in columns differ significantly at $p < 0.05$. * values in bold are the lowest (RDS, TS, SDI, and eGI) or highest (SDS, RS) in columns.

4. Discussion

This study investigated the impact of different polyphenols on the digestibility of various starches (wheat, rice, potato, and maize) when added before and after gelatinization. Epigallocatechin gallate was consistently the most effective in reducing RDS, TS, and (eGI) across all starch types (mostly in the dose of 20 mg). It was also the most efficient in terms of SDS and SDI in some cases. Kaempferol, naringenin, hesperidin, quercetin, and *trans*-ferulic acid were effective for specific starch types, with variations depending on whether they were added before or after gelatinization. The highest RS content was observed with different polyphenols across various starch types.

From a nutritional point of view, starch is classified into rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) [41]. RDS is the quantity of starch that is transformed into the constituent glucose molecules within 20 min following the initiation of enzyme digestion. RDS undergoes rapid digestion and absorption in the small intestine, resulting in a prompt increase in blood glucose levels. It was documented that considerable fluctuations in blood glucose levels can exert significant stress on the regulatory mechanisms of glucose homeostasis. Such stress can, in turn, give rise to adverse consequences at the cellular, tissue, and/or organ level and finally lead to obesity, insulin resistance, and diabetes [42–44].

SDS is the amount of starch that is converted into its constituent glucose molecules within 120 min of enzymatic digestion. It is slowly digested throughout the small intestine to provide a sustained release of glucose with a low initial blood glucose level. The potential health benefits of SDS include improvements in glucose metabolism, diabetes management, cognitive performance, and appetite control [42,43]. In regard to the impact of SDS on glucose metabolism, it is demonstrated that its consumption results in markedly slower and diminished fluctuations in blood glucose, insulin, and non-esterified fatty acids (NEFAs) in comparison to RDS. Additionally, this is accompanied by lower levels of circulating triacylglycerols and apolipoprotein B-100 and B-48 in triacylglycerol-rich lipoproteins. Furthermore, SDS is demonstrated to induce an elevation in glucagon-like peptide-1 (GLP-1) and glucose-dependent insulinotropic polypeptide (GIP) levels during the late postprandial phase [45–48].

The third kind of starch nutritional fraction is resistant starch (RS). It is not digested in the small intestine; instead, it is fermented by gut bacteria in the colon, resulting in the production of short-chain fatty acids (SCFAs). It is a dietary fiber, and its consumption is linked to many health benefits [42,43,49].

As food remains in the small intestine for approximately 4 h [50], total starch (TS) is the sum of starch digested during this period and RS. The starch digestion index (SDI) is a ratio of RDS and TS. Finally, the glycemic index (GI) is a measure that quantifies the rate of increase in blood glucose levels in response to the consumption of carbohydrate foods. Foods can be classified into three categories according to their GI values: low GI (≤ 55), middle GI (56–69), and high GI (≥ 70) foods [10,51]. The majority of starchy foods have a glycemic index value greater than 70 (e.g., white/whole wheat bread, white rice, boiled potatoes, and cornflakes) [9,52].

According to the literature, the optimal amount of polyphenols is 10 mg per day. This amount corresponds to the recommended daily intake of five portions of fruit and vegetables [53]. Doses twice and half the optimal amount, 20 mg and 5 mg, respectively, were also tested. In the case of starch, the following were also tested: wheat starch (a basic ingredient in bread making), maize starch (the most popular in the world), potato starch (the most popular in Poland), and rice starch (the most popular in Asian countries), so that the research would have a global scope. Each of the polyphenols was added separately to the starch before and after its pasting. From a technological point of view, it is more useful to check the parameters when the addition of the polyphenol follows the starch pasting. At the same time, from a chemical point of view, it is better to add the polyphenol before the starch is pasted since polyphenols are not resistant to high temperatures [54].

A review of the literature reveals a dearth of information regarding starch nutritional fraction content and the glycemic index value of wheat, rice, potato, and maize starch, particularly in the context of single polyphenols. It is known that the gelatinization process disrupts the structure of the starch, enabling a broader inhibition of enzyme activity and therefore increasing digestibility. Generally, pasted starch is digested at a more rapid rate than starch in granular, native form [55].

Only a limited number of studies have investigated the impact of heat treatment on starch digestibility and its glycemic index. Following the cooking process, the RDS, SDS, and RS values of potato starch were found to be 92.5%, 1.6%, and 5.9%, respectively [56]. For comparison, in the present study (in which the pasting process was also included), the RDS, SDS, and RS values of potato starch were found to be 91.4%, 2.5%, and 0.0%, respectively. In the case of gelatinized maize starch, the RDS, SDS, and RS values were reported to fall within the ranges from 81.8 to 95.3%, 0 to 16%, and 2.2 to 7.3%, respectively [57–60]. The present study yielded the following results: the RDS, SDS, and RS values were observed to be 96.7%, 1.6%, and 0.0%, respectively. No corresponding data are available regarding the digestibility of pasted wheat and rice starch. With regard to the estimated glycemic index of starch subsequent to gelatinization, as documented in the pertinent literature, the range for maize starch is 90.0–93.5, while the value for rice starch is 84.4 [22,57,61,62]. In the present study, the values were found to be 96.3 for maize starch and 94.6 for rice starch. With regard to wheat and potato starch, there is a paucity of data on their glycemic index.

In contrast to the present study, numerous studies have been conducted on the nutritional fractions of starch in native, granular form without prior pasting of the starch. The RDS values were as follows, according to the aforementioned sources: the starch content of the wheat, rice, potato, and maize samples was determined to be 36–71%, 32.4–74.2%, 1.0–9.9%, and 24.4–58.1%, respectively. The SDS content was found to be 26.3–64.0%, 23.4–60.1%, 2.0–15.2%, and 36.5–65.7%. The RS content was determined to be 0.0–9.6%, 0.0–23.8%, 74.9–93.1%, and 4.6–22.6%, respectively. The lowest RDS and the highest RS content were observed in potato starch. This phenomenon might be explained by the fact that the diameters of the potato starch granules are considerable, and the surfaces are smooth. Furthermore, it is widely acknowledged that potato starch granules are densely packed and exhibit minimal hydration [43]. As for native starch, the glycemic index values were as follows: 47.9–75.3, 61.3, 58.8, and 43.5 for maize, rice, wheat, and potato starch, respectively [57,63]. In general, the RDS and eGI values of gelatinized starch were observed to be lower in comparison to native starch, while the SDS and RS values were found to be higher.

In the preliminary study, the differences between the chemical structures of the tested polyphenols and the consequences of these differences on α -amylase activity and the establishment of polyphenol–amylose complexes were extensively described [37]. On this basis, epigallocatechin gallate was identified as the most potent inhibitor of starch digestion. The first difference in the chemical structure between epigallocatechin gallate and the rest of the tested polyphenols is the presence of hydroxyl groups. The polyphenol has the greatest number of them. The more hydroxyl groups polyphenol has, the more hydrogen bonds between them and amino acids of the enzyme can be created. As a consequence, the inhibition of α -amylase activity is stronger. Moreover, epigallocatechin gallate, as the only one from the tested polyphenols, contains a galloyl moiety. It provides additional hydroxyl groups, a benzene ring, and the C=O double bond. An extra benzene ring can create hydrophobic interactions within the enzyme's active site. The C=O double bond, when conjugated with the benzene ring, plays a role in electron delocalization. All this together forms a highly stable conjugated system that further enhances the inhibitory activity of the polyphenol. Additionally, in the molecular structure of epigallocatechin gallate, there is no substitution of -OCH₃ at -OH and no presence of the glycosylated form. It also increases the polyphenol's inhibitory activity on starch digestibility [37,64].

The current study also confirmed that epigallocatechin gallate exhibits the greatest inhibitory activity. The polyphenol demonstrated the greatest efficacy in reducing the RDS, TS, and eGI values of all the tested starches. Furthermore, the greatest outcomes were

typically observed when the highest dose tested (20 mg) was administered, despite the recommended daily intake of polyphenols being 10 mg [53]. The low value of RDS slows down the process of digestion because the lower the fraction is, the less glucose is released into the bloodstream rapidly after meal consumption [10,65]. Epigallocatechin gallate also had the greatest impact on lowering TS content, and it seems the reason for this is the establishment of non-digestible complexes between the polyphenol and starch granules [12]. Epigallocatechin gallate has a strong ability to alter the spatial configuration of starch, with highly consistent hydrogen bond occupancy and low binding free energy [66].

The highest efficiency in reducing RS content in wheat starch was observed with a dose of 5 mg of quercetin when the polyphenol was added after starch pasting ($p < 0.05$). The precise value was determined to be $3.33 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$ In the preliminary investigation wherein the digestibility of wheat starch was assessed through the measurement of RS (polyphenol addition after starch gelatinization), the exact value was established to be $3.89 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$ However, the preliminary study yielded a higher value when 5 mg of (+)catechin was added ($4.89 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$) [37], whereas the current study demonstrated an RS content of $0.68 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$ with the same quantity of (+)catechin. The inhibitory activity of both quercetin and (+)catechin was evaluated as being highly potent based on their molecular structure [37,64]. In the present study, (+)catechin was observed to be less effective than quercetin in the preliminary study. The addition of (+)catechin in a dose of 20 mg to rice starch after its pasting was found to be the most effective method for reducing RS ($p < 0.05$). Quercetin in a dose of 10 mg, on the other hand, was the most effective polyphenol for reducing SDS and SDI in rice starch when added after its pasting ($p < 0.05$). Additionally, the SDS of potato starch was reduced to the greatest extent by adding the polyphenol at a dose of 20 mg before pasting, while the RS of maize starch was reduced to the greatest extent by adding the polyphenol at a dose of 20 mg after pasting ($p < 0.05$). The highest RS content in wheat starch was recorded simultaneously with the addition of hesperidin at a dose of 10 mg after starch gelatinization ($3.31 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$, $p < 0.05$). This result is comparable to that obtained in the preliminary study, in which the highest RS content was observed for epigallocatechin gallate ($2.86 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$) and hesperidin, which yielded an equal result of $1.42 \text{ g} \cdot 100 \text{ g}^{-1} \text{ d.m.}$ [37].

The molecular structure of hesperidin indicates that it is a polyphenol with potent inhibitory activity, although not as strong as those previously mentioned, as is kaempferol. The most effective impact of SDS, RS, and SDI values of wheat starch was observed with the addition of kaempferol at a dose of 10 mg when administered prior to starch pasting ($p < 0.05$). Similarly, the addition of kaempferol exhibited the greatest inhibitory activity at the same dose when added after starch pasting in the case of the SDS value of potato starch ($p < 0.05$).

The weaker inhibitory activity abilities were inferred in the cases of naringenin and *p*-coumaric acid [37,64]. The most efficacious concentration of naringenin (20 mg) was observed for the RS content of maize starch when added prior to its pasting and for the SDS and SDI of potato starch when added subsequent to its pasting at a dose of 10 mg ($p < 0.05$). With regard to *p*-coumaric acid, it did not demonstrate the most effective results in any case. The polyphenol with the weakest inhibitory activity, based on its molecular structure, was *trans*-ferulic acid [37]. Nevertheless, the present study yielded the highest SDS value of rice (addition before starch pasting) and maize starch (addition after starch pasting) for *trans*-ferulic acid (10 mg) ($p < 0.05$).

In our study, we have proved that epigallocatechin gallate at a dose of 20 mg was the most effective polyphenol in reducing the value of the estimated glycemic index across all starch types. This finding constitutes useful and crucial implications for dietary recommendations, especially for people suffering from impaired carbohydrate metabolism, including type 2 diabetes.

The effect of polyphenol-rich foods (e.g., green tea, coffee, and berries) on glycemic control and insulin sensitivity has already been researched, particularly in relation to diabetes. Concerning green tea, the results are mixed, with some studies showing no effect on glycemic markers, while others suggested modest reductions in fasting glucose. Studies indicated

that coffee, especially due to chlorogenic acid, may influence glucose absorption and gastrointestinal hormone secretion, but overall evidence of its effect on glucose homeostasis is limited. Berries may delay glucose absorption and reduce postprandial insulin responses, but their overall effect on long-term glycemic control is not well-established [67]. Therefore, it would be interesting to conduct clinical research on the impact of the starches with added polyphenols (that gave the best results in the present study) on postprandial glycemia.

The possible limitations of the conducted study may include the fact that the food consumed is usually a mixture of many nutrients (i.e., protein, fats, dietary fiber), not just starch, and those substances may affect the rate of starch digestion. Moreover, the tested polyphenols differ in their solubility and hence may have different bioavailability in the living organisms. Most of those tested were hardly soluble in water. For this reason, DMSO was used, but it is impossible to apply such a solvent in the food production process. And finally, there is a huge range of polyphenols found in food products, and it is impossible to test all of them at the same time. It is even probable that the most popular foods may not necessarily be the most effective ones in terms of their ability to inhibit starch digestion.

5. Conclusions

The present study indicated that there were differences between various polyphenols in their ability to reduce starch digestibility and the estimated glycemic index ($p < 0.05$). For all the starches tested (wheat, rice, potato, and maize), the best inhibitory effect on starch digestibility and lowering of the glycemic index was obtained with the addition of epigallocatechin gallate at the highest dose tested: 20 mg. Epigallocatechin gallate proved to be the most effective polyphenol in reducing RDS, TS, and eGI across all starch types (mainly at a dose of 20 mg). Furthermore, it exhibited the most efficient results in certain cases with regard to SDS and SDI. The polyphenol demonstrated the greatest efficacy in wheat, rice, and potato starch when added prior to the starch being gelatinized and in maize starch when added after starch gelatinization. The continuation of the research is significant regarding the influence of different types of starches with polyphenols on the glycemic index and the bioavailability of the polyphenolic compounds tested on living organisms, including human volunteers, together with an investigation of some physicochemical properties and a more thorough inspection on the potential antioxidant and cytotoxic properties.

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