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Research Article

Assessment of Protein Quality in Gluten-Free and Gluten-Containing Food Products: Insights from the PDCAAS Method

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ABSTRACT

This study aims to investigate the protein quality of gluten-free products and gluten-containing products using the Protein Digestibility Corrected Amino Acid Score (PDCAAS) method. Twenty gluten-free and twenty gluten-containing products were selected, including various types of flour, bread, pasta, crackers, biscuits, and cakes. Amino acid contents were obtained from TURKOMP, USDA, and literature research. Protein contents of products were between 2.63-52.5 g/100g and 2.4-13.4 g/100 g for gluten-free and gluten-containing products, respectively. PDCAAS scores of gluten-free products and gluten-containing products were found to be between 0.2% and 100%, and 34.4% and 100%, respectively. Peanut flour, soy flour, and chickpea flour can be a preferable alternative for gluten-free recipes with their high protein content. Gluten-free products made from rice flour and sorghum flour have been found to have the highest protein quality. In conclusion, the amount and quality of protein in gluten-free products can vary depending on the type of protein sources used. In a gluten-free diet, products with high protein quantity and quality should be preferred.

Keywords: Gluten, Gluten-free products, Gluten-containing products, Protein quality, PDCAAS

Introduction

Thousands of years ago, with the development of agriculture, significant changes occurred in human nutrition. Along with these changes, cereal products, which have a significant place in nutrition today, have emerged (Alt et al., 2022). Recently, the effect of a protein complex called gluten, found in wheat, barley and rye, on diseases is a current research topic (Shewry, 2019). These diseases include celiac disease, gluten ataxia, dermatitis herpetiformis, wheat allergy, and gluten sensitivity. The symptoms of these diseases, which are triggered by gluten consumption, can be reduced with a gluten-free diet (Smolinska et al., 2025). A gluten-free diet is a diet that eliminates some cereals (wheat, barley and rye), which are among the plant protein sources, and all kinds of foods produced from them (Aljada et al., 2021). Today, a gluten-free diet is preferred by both healthy individuals and those with gluten-related diseases, thereby increasing the demand for gluten-free products (Sabença et al., 2021). The increasing interest in gluten-free products also underscores the importance of assessing the quality of their nutrient profile. Gluten is the primary protein in wheat, and studies have reported that gluten-free products contain less protein than their gluten-containing counterparts (Miranda et al., 2014; Missbach et al., 2015; Sevim et al., 2023; Wu et al., 2015). Although determining the protein content of gluten-free products is an important research topic, to our knowledge, the protein quality of these products has not been studied well.

Protein quality is an indicator of the amount of essential amino acids in foods, and essential amino acids for humans can be met from dietary proteins. The amino acid profile and digestibility of proteins in gluten-free products may differ from those in gluten-free sources, and both protein quality and quantity should be assessed. (Leser, 2013). Investigating protein quality in gluten-free products is crucial to improving the nutritional quality of people with celiac disease and gluten intolerance. In particular, it is necessary to find solutions to the problem of protein deficiency that can be seen in gluten-free diets and to evaluate the effectiveness of alternative protein sources. For this reason, the present study aimed to determine the protein quality of gluten-free and equivalent gluten products theoretically using the PDCAAS (Protein Digestibility-Corrected Amino Acid Score) method, as recommended by the World Health Organisation (WHO) and the Food and Agriculture Organisation (FAO, 1991).

Materials and Methods

Data Selection

Within the scope of the study, a total of 40 products — 20 gluten-free and 20 gluten-containing — were selected to determine protein quality using the PDCAAS method. The selected gluten-free and gluten-containing products, along with their references for protein and amino acid amounts, were obtained from TURKOMP (Turkish Food Composition Database), USDA (United States Department of Agriculture), or studies in the literature, and are presented in Table 1. Nutritional data on protein and amino acid composition of the products were primarily obtained from the TURKOMP. As the national database, TURKOMP was given initial priority to reflect local nutritional characteristics. However, due to the limited availability of gluten-free product data in TURKOMP, additional information was gathered from the USDA Food Data Central and peer-reviewed literature. This approach was adopted to ensure the inclusion of a wide variety of gluten-free products and to enable a comprehensive comparison with gluten-containing products.

Calculation of Protein Quality

In this study, the PDCAAS (Protein Digestibility Corrected Amino Acid Score) method recommended by FAO and WHO was used to determine the protein quality of gluten-free and gluten products (FAO/WHO, 1991). For the calculation, first, the limiting amino acid (the amino acid with the lowest score) of the products was determined by calculating the amino acid scores of the products. Then, these values were multiplied by the protein digestibility factor (actual faecal digestibility) determined for the products and the PDCAAS values of the products were calculated. Since PDCAAS ranges from 0 to 100, the scores of products exceeding 100 were corrected to 100. Values close to 100 indicate that the protein quality of the product is high, while values far away from 100 indicate that the protein quality of the product is low (Lee et al., 2016). The formula for the PDCAAS method (Schaafsma, 2005) is as follows:

$$\textbf{PDCAAS}\ \% = \frac{\text{mg of first limiting amino acid in 1g test protein}}{\text{mg of the same amino acid in 1 g reference protein}} \text{ x True fecal digestibility (\%)}$$

Table 1. The types of gluten-free and gluten-containing products.

Number	Product Type	Reference
	Gluten Free Products	
1	Corn flour	TURKOMP
2	Brown rice flour	USDA
3	White rice flour	USDA
4	Soy flour	USDA
5	Potato flour	USDA
6	Peanut flour	USDA
7	Quinoa flour	(Iovan et al., 2016)
8	Chickpea flour	(Nosworthy et al., 2020)
9	Bread with brown rice flour	USDA
10	Bread with rice and sorghum flour	USDA
11	Pasta with corn flour	USDA
12	Pasta with corn and rice flour	USDA
13	Pasta with corn and quinoa flour	USDA
14	Pasta with brown rice flour	USDA
15	Crackers with potato flour	USDA
16	Crackers with corn and potato flour	(Kamel et al., 2020)
17	Crackers with corn, potato and soy flour	(Kamel et al., 2020)
18	Crackers with corn, potato and chickpea flour	(Kamel et al., 2020)
19	Cake with rice flour	(Sung et al., 2020)
20	Biscuits with rice and quinoa flour	(Iovan et al., 2016)
	Gluten-Containing Products	
21	Wheat flour	USDA
22	Barley flour	TURKOMP
23	Rye flour	TURKOMP
24	Semolina	TURKOMP
25	White bread	TURKOMP
26	Rye bread	TURKOMP
27	Whole wheat bread	TURKOMP
28	Multigrain bread	USDA
29	Plain pasta	USDA
30	Spinach pasta	USDA
31	Whole wheat pasta	USDA
32	Crackers with wheat flour	USDA
33	Crackers with rye flour	USDA
34	Crackers with whole wheat flour	USDA
35	Multigrain cracker	USDA
36	Fruit cake	USDA
37	Chocolate cake	USDA
38	Sponge cake	USDA
39	Mixed grain biscuit	USDA
40	Baby biscuit	TURKOMP

Calculation of Amino Acid Scores

In order to determine the amino acid score of gluten-free and gluten-containing products, 11 amino acids (generally essential amino acids) out of 20 amino acids (histidine, isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan and valine) were included in the calculation. The sum of methionine and cysteine from sulfur amino acids (SAA) and the sum of phenylalanine and tyrosine from aromatic amino acids (AAA) were used in the calculation. The amounts of these amino acids in grams of protein (mg) were then calculated, and these amounts were divided by the reference values for the age groups to obtain the amino acid

scores. The amino acid requirement reference scoring model, categorised by age groups, is presented in Table 2. In general, since gluten-related disorders can be observed in all age groups, the FAO recommends using reference values for children, adolescents, and adults aged 3-10 years. Therefore, reference values for the 3-10 year age group were used in this study (Leser, 2013). The amino acid with the lowest score in the products was determined as the limiting amino acid of that product, and this score was used to calculate the PDCAAS value. Amino acid score (AAS) calculation formula (Yang et al., 2023) is as follows:

$$\textbf{Amino Acid Score (AAS)} = \frac{\text{mg of amino acid in 1 g test protein}}{\text{mg of amino acid in 1 g reference protein}}$$

Determination of Protein Digestibility Factors

When calculating protein quality by the PDCAAS method, the limiting amino acid score is multiplied by the protein digestibility factor (actual faecal digestibility). Therefore, the protein digestibility factors of gluten-free products for which PDCAAS values were calculated in this study were determined by reviewing the literature. The digestibility factors of gluten-free products and gluten-containing products and their references are given in Table 3.

Results and Discussion

Protein (g) and amino acid amounts (mg) per 100 g of gluten-free and gluten-containing products included in the study were obtained from TURKOMP, USDA or studies in the literature, which are presented in Table 4. As given, the protein content of gluten-free products ranged from 2.63 to 52.2 g/100g, with an average value of 11.23 g/100g. The gluten-free product with the highest protein content per 100g was peanut flour, at 52.20g, followed by soy flour at 51.50g, chickpea flour at 21.15g, and quinoa flour at 13.92g. The gluten-free product with the lowest protein content was corn flour pasta, at 2.63 g, followed by corn and rice flour pasta at 3.20 g, corn and quinoa flour pasta at 3.23 g, and brown rice flour pasta at 3.46 g, respectively. The protein content of gluten-containing products ranged from 2.4 to 13.4 g/100g, with an average value of 7.57 g/100g. The gluten-containing product with the highest protein content per 100g is multigrain bread, at 13.40g, followed by whole wheat bread at 10.79g, rye flour at 10.61g, and whole wheat flour crackers at 10.60g. The gluten-containing product with the lowest protein content was chocolate cake, at 2.40 g, followed by fruit cake at 2.90 g, baby biscuit at 4.10 g, spinach pasta at 5.06 g, and plain pasta at 5.15 g. In the flour category, peanut flour, the product with the highest protein content, is classified in the gluten-free group, while corn flour, the product with the lowest protein content, is not. In the cake category, the product with the highest protein content, cake, is in the gluten-free group, while chocolate cake, the product with the lowest protein content, is also in this group. In the bread, pasta and cracker categories, multigrain bread, whole wheat pasta and whole wheat flour crackers with the highest protein content were in the gluten-free group, while brown rice flour bread, rice and sorghum flour bread, corn flour pasta, and potato flour crackers with the lowest protein content are in the gluten-free group. On the other hand, in the biscuit category, rice and quinoa flour biscuits with the highest protein content are in the gluten-free group, while baby biscuits with the lowest protein content are in the gluten group. These results suggest that the protein content of gluten-free products is not always lower than that of their gluten counterparts and, in some cases, may be higher.

Table 2. Amino acid requirement reference scoring model by age groups (mg/g protein) (FAO, 2013)

Age (year)	His	İle	Leu	Lys	SAA	AAA	Thr	Trp	Val
0.5	20	32	66	57	27	52	31	8.5	43
1-2	18	31	63	52	25	46	27	7	41
3-10	16	30	61	48	23	41	25	6.6	40
11-14	16	30	61	48	23	41	25	6.6	40
15-18	16	30	60	47	23	40	24	6.3	40
>18	15	30	59	45	22	38	23	6	39

Table 3. The protein digestibility factors (PDF) of gluten-free and gluten-containing products

	Product Name	PDF (%)	Reference
	Gluten Free Products		
1	Corn flour	85	FAO, 2007
2	Brown rice flour	95	(Pedersen & Eggum, 1983)
3	White rice flour	88	FAO, 2007
4	Soy flour	86	FAO, 2007
5	Potato flour	73.3	(Gahlawat & Sehgal, 1998)
6	Peanut flour	96	(Bodwell et al., 1980)
7	Quinoa flour	95	(Ruales et al., 2002)
8	Chickpea flour	86.6	(Nosworthy et al., 2020)
9	Bread with brown rice flour	95	(Pedersen & Eggum, 1983)
10	Bread with rice and sorghum flour	85	FAO/WHO/UNU, 1985
11	Pasta with corn flour	85	FAO, 2007
12	Pasta with corn and rice flour	85	FAO/WHO/UNU, 1985
13	Pasta with corn and quinoa flour	85	FAO/WHO/UNU, 1985
14	Pasta with brown rice flour	95	(Pedersen & Eggum, 1983)
15	Crackers with potato flour	73.3	(Gahlawat & Sehgal, 1998)
16	Crackers with corn and potato flour	85	FAO/WHO/UNU, 1985
17	Crackers with corn, potato and soy flour	85	FAO/WHO/UNU, 1985
18	Crackers with corn, potato and chickpea flour	85	FAO/WHO/UNU, 1985
19	Cake with rice flour	88	FAO, 2007
20	Biscuits with rice and quinoa flour	85	FAO/WHO/UNU, 1985
	Gluten-Containing Products		
21	Wheat flour	96	FAO, 2007
22	Barley flour	87.4	(Pedersen & Eggum, 1983)
23	Rye flour	83.6	(Pedersen & Eggum, 1983)
24	Semolina	86	FAO, 2007
25	White bread	96	FAO, 2007
26	Rye bread	83.6	(Pedersen & Eggum, 1983)
27	Whole wheat bread	86	FAO, 2007
28	Multigrain bread	85	FAO/WHO/UNU, 1985
29	Plain pasta	86	FAO, 2007
30	Spinach pasta	86	FAO, 2007
31	Whole wheat pasta	86	FAO, 2007
32	Crackers with wheat flour	96	FAO, 2007
33	Crackers with rye flour	83.6	(Pedersen & Eggum, 1983)
34	Crackers with whole wheat flour	86	FAO, 2007
35	Multigrain cracker	85	FAO/WHO/UNU, 1985
36	Fruit cake	85	FAO/WHO/UNU, 1985
37	Chocolate cake	85	FAO/WHO/UNU, 1985
38	Sponge cake	85	FAO/WHO/UNU, 1985
39	Mixed grain biscuit	85	FAO/WHO/UNU, 1985
40	Baby biscuit	85	FAO/WHO/UNU, 1985

Table 4. The protein (g) and amino acid amounts (mg) in 100 grams of the gluten-free and gluten-containing products

Number	Product Type	Protein	His	Ile	Leu	Lys	SAA	AAA	Thr	Trp	Val
	Gluten Free Products										
1	Corn flour	5.44	71	278	532	206	155	648	112	105	301
2	Brown rice flour	7.23	184	306	598	276	207	644	265	92	424
3	White rice flour	5.95	149	244	488	207	198	631	210	72	348
4	Soy flour	51.50	1270	2280	3830	313	1013	4230	2040	683	2350
5	Potato flour	6.90	166	299	425	413	142	540	280	115	356
6	Peanut flour	52.50	1320	1840	3380	1870	976	4820	1790	507	2190
7	Quinoa flour	13.92	542	430	944	877	587	1122	614	266	511
8	Chickpea flour	21.15	640	890	1750	1450	540	1820	800	230	960
9	Bread with brown rice flour	5.40	130	250	460	350	260	500	230	80	280
10	Bread with rice and sorghum flour	5.40	130	250	460	350	260	500	230	80	280
11	Pasta with corn flour	2.63	80	94	322	74	79	236	99	19	133
12	Pasta with corn and rice flour	3.20	92	103	452	164	108	319	103	20	103
13	Pasta with corn and quinoa flour	3.23	89	89	355	158	94	266	99	20	108
14	Pasta with brown rice flour	3.46	84	114	264	208	114	323	109	40	134
15	Crackers with potato flour	3.52	17	27	56	32	17	53	25	8	34
16	Crackers with corn and potato flour	4.61	173	85	197	80	138	254	160	136	178
17	Crackers with corn, potato and soy flour	9.36	252	312	742	386	428	742	327	371	430
18	Crackers with corn, potato and chickpea flour	6.13	154	199	472	236	254	463	191	229	254
19	Cake with rice flour	3.55	0.2	0.8	1.3	0.5	0.2	1.0	5.2	0.1	0.4
20	Biscuits with rice and quinoa flour	9.86	216	363	674	352	331	850	317	110	488
Average Protein Content		11.23									
	Gluten-Containing Products										
21	Wheat flour	10.30	230	357	710	228	293	832	281	127	415
22	Barley flour	8.22	180	247	621	383	392	788	328	157	320
23	Rye flour	10.61	189	538	990	363	270	1228	192	136	588
24	Semolina	8.66	199	225	526	226	194	659	160	161	269
25	White bread	9.41	193	148	657	324	198	689	180	77	367
26	Rye bread	10.01	118	414	827	377	377	943	392	67	475
27	Whole wheat bread	10.79	303	379	631	226	381	768	252	125	422
28	Multigrain bread	13.40	198	323	556	289	226	623	271	124	397
29	Plain pasta	5.15	103	197	348	97	151	381	134	65	217
30	Spinach pasta	5.06	107	219	365	151	160	401	158	67	245
31	Whole wheat pasta	5.99	140	232	409	133	160	454	161	77	259
32	Crackers with wheat flour	7.30	190	306	586	190	238	571	265	105	386
33	Crackers with rye flour	7.90	179	318	556	300	199	571	285	92	404
34	Crackers with whole wheat flour	10.60	238	364	703	271	284	674	301	141	465
35	Multigrain cracker	7.10	168	237	481	182	196	532	193	88	291
36	Fruit cake	2.90	71	121	206	121	90	235	102	42	144
37	Chocolate cake	2.40	46	109	180	148	67	172	104	30	124
38	Sponge cake	5.40	119	251	419	297	186	450	213	72	281
39	Mixed grain biscuit	6.10	138	214	424	143	173	487	169	76	251
40	Baby biscuit	4.10	69	242	459	184	161	507	97	68	280

*The reference sources for each product are listed in Table 1.

The amino acid scores, protein digestibility-corrected amino acid score (PDCAAS), and PDCAAS values of the gluten-free products and gluten-containing products included in the study are presented in Table 5. The average PDCAAS value of gluten-free products was 66.37% and the products with the highest PDCAAS values were brown rice flour bread and rice and sorghum flour bread with 100%, followed by chickpea flour, brown rice flour pasta and quinoa flour with 96.1%, 91.2% and 87.4%, respectively. The gluten-free product with the lowest PDCAAS value was rice flour cake, at 0.2%, followed by potato flour crackers at 13.2%, corn and potato flour crackers at 30.6%, and corn flour pasta at 49.3%. According to these results, among the gluten-free products, the product with the highest protein quality was brown rice flour bread and rice and sorghum flour bread, while the product with the lowest protein quality was rice flour cake.

Caire-Juvera et al. (2013) found that lysine was the limiting amino acid in cereal-based products. Similarly, in this study,

lysine was the amino acid with the lowest amino acid score with 0.78 in corn flour, 0.80 in brown rice flour, 0.72 in white rice flour, 0.58 in corn flour pasta, 0.18 in potato flour crackers, 0.36 in corn and potato flour crackers, 0.86 in corn, potato and soy flour crackers, 0.80 in corn, potato and chickpea flour crackers, and 0.74 in rice and quinoa flour biscuits. The limiting amino acid in peanut flour examined in this study was found to be lysine, with a concentration of 0.75 (Caire-Juvera et al., 2013). Boye et al. found that the limiting amino acid in peanut flour was threonine, while the limiting amino acid in peanut flour was lysine. This difference is thought to be due to variations in the selected peanuts (differences in the type and genetics of peanuts) and the treatments applied to them (such as cultivation techniques and heat treatment) (Boye et al., 2012).

Table 5. Amino acid scores, protein digestibility factors (PDF) and PDCAAS values of gluten-free and gluten-containing products

Number	Product Type	PDF (%)	His	Ile	Leu	Lys	SAA	AAA	Thr	Trp	Val	PDCAAS (%)
Gluten Free Products												
1	Corn flour	85	0.81	1.70	1.60	**0.78**	1.24	2.90	0.82	2.92	1.38	66.3
2	Brown rice flour	95	1.59	1.41	1.35	**0.80**	1.24	2.17	1.46	1.93	1.46	76.0
3	White rice flour	88	1.56	1.36	1.34	**0.72**	1.44	2.58	1.41	1.83	1.46	63.4
4	Soy flour	86	1.54	1.47	1.22	1.27	**0.85**	2.00	1.58	2.01	1.14	73.1
5	Potato flour	73.3	1.50	1.44	1.01	1.24	**0.90**	1.90	1.62	2.52	1.30	66.0
6	Peanut flour	96	1.58	1.17	1.06	**0.75**	0.81	2.25	1.37	1.47	1.05	72.0
7	Quinoa flour	95	2.43	1.03	1.11	1.31	1.83	1.96	1.76	2.89	**0.92**	87.4
8	Chickpea flour	86.6	1.89	1.40	1.35	1.42	**1.11**	2.09	1.51	1.64	1.13	96.1
9	Bread with brown rice flour	95	1.50	1.54	1.40	1.35	2.10	2.25	1.70	2.24	**1.29**	100
10	Bread with rice and sorghum flour	85	1.50	1.54	1.40	1.35	2.10	2.25	1.70	2.24	**1.29**	100
11	Pasta with corn flour	85	1.90	1.19	2.01	**0.58**	1.30	2.18	1.50	1.10	1.26	49.3
12	Pasta with corn and rice flour	85	1.80	1.07	2.31	1.06	1.46	2.43	1.28	0.94	**0.80**	68.0
13	Pasta with corn and quinoa flour	85	1.72	0.91	1.80	1.01	1.26	2.01	1.22	0.93	**0.83**	70.5
14	Pasta with brown rice flour	95	1.51	1.10	1.25	1.25	1.43	2.27	1.26	1.75	**0.96**	91.2
15	Crackers with potato flour	73.3	0.30	0.25	0.26	**0.18**	0.21	0.36	0.28	0.34	0.24	13.2
16	Crackers with corn and potato flour	85	2.34	0.61	0.70	**0.36**	1.30	1.34	1.38	4.47	0.96	30.6
17	Crackers with corn, potato and soy flour	85	1.68	1.11	1.30	**0.86**	1.98	1.93	1.40	6.01	1.15	73.1
18	Crackers with corn, potato and chickpea flour	85	1.57	1.08	1.26	**0.80**	1.80	1.84	1.24	5.66	1.03	68.0
19	Cake with rice flour	88	0.003	0.007	0.006	0.003	**0.002**	0.007	0.058	0.004	0.003	0.2
20	Biscuits with rice and quinoa flour	85	1.37	1.22	1.12	**0.74**	1.46	2.10	1.28	1.69	1.24	63.0
Average PDCAAS												66.37
Gluten-Containing Products												
21	Wheat flour	96	1.40	1.15	1.13	**0.46**	1.23	1.97	1.10	1.87	1.01	44.2
22	Barley flour	87.4	1.37	1.00	1.24	**0.97**	2.07	2.34	1.60	2.90	**0.97**	85.0
23	Rye flour	83.6	1.11	1.70	1.53	**0.71**	1.10	2.82	0.72	1.94	1.38	59.3
24	Semolina	86	1.43	0.86	0.99	**0.54**	0.97	1.85	0.74	2.81	0.77	46.4
25	White bread	96	1.28	**0.52**	1.14	0.71	0.91	1.78	0.76	1.24	0.97	50.0
26	Rye bread	83.6	**0.73**	1.37	1.35	0.78	1.63	2.30	1.56	1.01	1.18	61.0
27	Whole wheat bread	86	1.75	1.17	0.96	**0.43**	1.53	1.73	0.93	1.75	0.98	37.0
28	Multigrain bread	85	0.92	0.80	0.68	**0.45**	0.73	1.13	0.81	1.40	0.74	38.2
29	Plain pasta	86	1.25	1.27	1.11	**0.40**	1.27	1.80	1.04	1.91	1.05	34.4
30	Spinach pasta	86	1.32	1.44	1.18	**0.62**	1.37	1.93	1.24	2.00	1.21	53.3
31	Whole wheat pasta	86	1.46	1.30	1.12	**0.46**	1.16	1.84	1.07	1.94	1.08	39.5
32	Crackers with wheat flour	96	1.62	1.40	1.31	**0.54**	1.41	1.90	1.45	2.17	1.32	52.0
33	Crackers with rye flour	83.6	1.41	1.34	1.15	**0.80**	1.10	1.76	1.44	1.76	1.28	67.0
34	Crackers with whole wheat flour	86	1.40	1.14	1.08	**0.53**	1.16	1.55	1.13	2.01	1.10	45.6
35	Multigrain cracker	85	1.48	1.11	1.11	**0.53**	1.20	1.82	1.08	1.87	1.02	45.0
36	Fruit cake	85	1.53	1.40	1.16	**0.87**	1.35	1.97	1.40	2.20	1.24	74.0
37	Chocolate cake	85	**1.19**	1.51	1.23	1.28	1.21	1.74	1.73	1.90	1.30	100
38	Sponge cake	85	1.37	1.55	1.27	**1.14**	1.49	2.03	1.57	2.01	1.30	97.0
39	Mixed grain biscuit	85	1.41	1.17	1.14	**0.48**	1.23	1.95	1.10	1.88	1.02	41.0
40	Baby biscuit	85	1.05	1.96	1.83	**0.93**	1.70	3.01	0.94	2.51	1.70	79.0
Average PDCAAS												57.44

Table 6. PDCAAS values of gluten-free and gluten-containing products

Number	Product Type	PDCAAS (%)
	Gluten Free Products	
1	Corn flour	66.3
2	Brown rice flour	76
3	White rice flour	63.4
4	Soy flour	73.1
5	Potato flour	66
6	Peanut flour	72
7	Quinoa flour	87.4
8	Chickpea flour	96.1
9	Bread with brown rice flour	100
10	Bread with rice and sorghum flour	100
11	Pasta with corn flour	49.3
12	Pasta with corn and rice flour	68
13	Pasta with corn and quinoa flour	70.5
14	Pasta with brown rice flour	91.2
15	Crackers with potato flour	13.2
16	Crackers with corn and potato flour	30.6
17	Crackers with corn, potato and soy flour	73.1
18	Crackers with corn, potato and chickpea flour	68
19	Cake with rice flour	0.2
20	Biscuits with rice and quinoa flour	63
	Gluten-Containing Products	
21	Wheat flour	44.2
22	Barley flour	85
23	Rye flour	59.3
24	Semolina	46.4
25	White bread	50
26	Rye bread	61
27	Whole wheat bread	37
28	Multigrain bread	38.2
29	Plain pasta	34.4
30	Spinach pasta	53.3
31	Whole wheat pasta	39.5
32	Crackers with wheat flour	52
33	Crackers with rye flour	67
34	Crackers with whole wheat flour	45.6
35	Multigrain cracker	45
36	Fruit cake	74
37	Chocolate cake	100
38	Sponge cake	97
39	Mixed grain biscuit	41
40	Baby biscuit	79

Legumes and cereals are considered complementary proteins as they complement each other's essential amino acid deficiencies. Legumes are rich in lysine and limiting in sulfur amino acids (methionine and cysteine), while cereals are the opposite (Shewry, 2019). Similarly, Erbersdobler et al. found that legumes are rich in lysine (Erbersdobler et al., 2017), and Caire-Juvera et al. found that the limiting amino acid in legumes is sulfur amino acids (SAA) (Caire-Juvera et al., 2013). Within the scope of our study, flours made from chickpea and soybean, which are legumes rich in protein, were examined. Similar to the literature, the limiting amino acid in both flours was found to be SAA, with values of 1.11 and 0.85, respectively. In this study, the limiting amino acids in potato flour and rice flour cake belonged to the sulfur amino acids (methionine and cysteine), with concentrations of 0.90% and 0.002%, respectively. Among the remaining products, the lowest amino acid score was found in valine, with values of 0.92 in quinoa flour, 1.29 in brown rice flour bread and rice, and sorghum flour bread, 0.80 in corn and rice flour pasta, 0.83 in corn and quinoa flour pasta, and 0.96 in brown rice flour pasta. According to these results, the limiting amino acids in gluten-free products were identified as lysine, sulfurous amino acids (methionine and cysteine), or valine. Among these amino acids, lysine was determined as the limiting amino acid in 10 gluten-free products, sulfurous amino acids (methionine + cysteine) in 4 products and valine in 6 gluten-free products.

The average PDCAAS value of gluten-containing products is 57.44%. The product with the highest PDCAAS value is chocolate cake, at 100%, followed by cake, barley flour, and baby biscuit, with values of 97%, 85%, and 79%, respectively. The product with the lowest PDCAAS value was plain pasta, at 34.4%, followed by whole wheat bread at 37%, multigrain bread at 38.2%, and whole wheat pasta at 39.5%. According to these results, the product with the highest protein quality among gluten products was chocolate cake, while the product with the lowest protein quality was plain pasta.

Abdel-Aal and Hucl et al. found lysine to be the limiting amino acid in cereals. Similarly, in this study, 0.46 in wheat flour, 0.71 in rye flour, 0.54 in semolina, 0.43 in whole wheat bread, 0.45 in multigrain bread, 0.40 in plain pasta, 0.62 in spinach pasta, The amino acid with the lowest amino acid score was lysine with 0.46 in whole wheat pasta, 0.54 in wheat flour crackers, 0.80 in rye flour crackers, 0.53 in whole wheat flour and multigrain crackers, 0.87 in fruit cakes, 1.14 in sponge cake, 0.48 in mixed grain biscuits, 0.93 in baby biscuits. In barley flour, the lowest amino acid scores were observed for both lysine and valine, with scores of 0.97. Among the remaining products, the lowest amino acid score was observed in rye bread, with a score of 0.73, and in chocolate cake, with a score of 1.19. In white bread, the lowest score belonged to isoleucine, at 0.52. According to these results, the limiting amino acids in gluten products were determined as lysine, lysine and valine, histidine or isoleucine and among these amino acids, lysine was determined as the limiting amino acid of 16 gluten products, lysine and valine 1, histidine 2 and isoleucine 1 (Abdel-Aal & Hucl, 2002).

The PDCAAS values of gluten-free and gluten-containing products, whose protein quality was evaluated according to the PDCAAS method, are shown in Table 6. As seen, among the gluten-free and gluten-containing products, the products with the highest PDCAAS value were brown rice flour bread, rice and sorghum flour bread and chocolate cake with 100%, followed by sponge cake with 97%, chickpea flour with 96.1%, brown rice flour pasta with 91.2% and quinoa flour with 87.4%. The product with the lowest PDCAAS value was rice flour cake with a 0.2%, followed by potato flour crackers with 13.2%, corn and potato flour crackers with 30.6%, plain pasta with 34.4%, whole wheat bread with 37%, multigrain bread with 38.2% and whole wheat pasta with 39.5%. According to these results, among the gluten-free and gluten-containing products, brown rice flour bread, rice and sorghum flour bread, and chocolate cake had the highest protein quality. In contrast, rice flour cake had the lowest protein quality.

The average PDCAAS was higher in gluten-free products (66.37%) than in gluten products (57.44%). When PDCAAS values were compared across product categories, chickpea flour had the highest protein quality, with a value of 96.1% in the flour category. In contrast, wheat flour had the lowest protein quality, with a value of 44.2%. Similar to our results, in a study by Culetu et al. (2021), the PDCAAS value of chickpea flour was found to be 97% (Culetu et al., 2021), and in another study (Köseoğlu, 2019), the PDCAAS value of wheat flour was found to be 56%. According to both results, the protein quality of chickpea flour is considered high, while the protein quality of wheat flour is considered low. In addition, the PDCAAS value of corn flour was found to be 66.3% in this study, while it was found to be 47% in another study (Culetu et al., 2021). Differences in results may be attributed to variations in product type and calculation method.

In the present study, the PDCAAS value of white rice flour was found to be 63.4%, while that of brown rice flour was found to be 76%. In another study by Culetu et al. (2021, PDCAAS values of white and brown rice flours were found to be 56% and 61%, respectively. In both studies, brown rice flour was found to have higher protein quality than white rice

flour. In this study, the PDCAAS value of quinoa flour was 87.4% and the PDCAAS value of soy flour was 73.1%. Similar to our study, the PDCAAS value of quinoa flour was found to be 85% in a study by Culetu et al. (2021), and the PDCAAS value of soy flour was found to be 82.21% in a study by Stone et al. (. According to the results, both flours are considered gluten-free sources of flour with good protein quality.

According to Table 6, in the bread category, brown rice flour bread and rice and sorghum flour bread had the highest protein quality, at 100%, while whole wheat bread had the lowest protein quality, at 37%. In addition, Guerrero-Elizarraraz, Mares-Mares, and Sosa-Morales (2017) found that the PDCAAS value of gluten-free bread with rice and soy flour was 97.74%, while the PDCAAS value of gluten-free bread with wheat flour was 49.4%(de la Luz Guerrero-Elizarraráz et al., 2017). Similarly, in this study, the PDCAAS value of wheat flour gluten bread (white bread) was found to be 50%, whereas the PDCAAS values of brown rice flour gluten-free bread and rice and sorghum flour gluten-free bread were found to be 100%. According to these results, it was observed that gluten-free breads have very high protein quality, while gluten breads have low protein quality. It is thought that gluten-free breads with high protein quality will be a good choice for general consumers. In the pasta category, brown rice flour pasta had the highest protein quality, at 91.2%, while plain pasta had the lowest protein quality, at 34.4%. In a study comparing gluten and gluten-free pasta (Rachman et al., 2023), the PDCAAS value of gluten-free pasta with durum wheat flour was 63% and the PDCAAS value of gluten-free pasta with banana and cassava flour was 4%. In this study, the PDCAAS value of all gluten-free pastas (49.3% with corn flour, 68% with corn and rice flour, 70.5% with corn and quinoa flour, 91.2% with brown rice flour) was higher than the PDCAAS value of all gluten pasta except spinach pasta (34.4% with plain, 53.3% with spinach, 39.5% with whole wheat flour). It is thought that some differences in protein quality calculation (such as the use of amino acid reference values and digestibility factor for different age groups) and/or differences in the types and amounts of products (such as flours and protein additions) used in the pastas are effective in this difference between the studies. According to the same study (Rachman et al., 2023), when egg white protein or soy protein isolate was added to gluten-free pasta at concentrations of 5%, 10%, and 15%, the PDCAAS value of the gluten-free pasta varied between 68% and 94% and demonstrated higher protein quality than gluten pasta.

In the cracker category, the cracker with the highest protein quality was the corn, potato, and soy flour cracker, with 73.1%, and the cracker with the lowest protein quality was the potato flour cracker, with 13.2%. In the cake category, the chocolate cake had the highest protein quality, at 100%, while the rice flour cake had the lowest protein quality, at 0.2%. In the biscuit category, the biscuit with the highest protein quality was the baby biscuit, at 79%, and the biscuit with the lowest protein quality was the mixed grain biscuit, at 41%.

According to these results, the products with the highest protein quality in the flour, bread and pasta categories are found among gluten-free products. In contrast, the products with the lowest protein quality are found among gluten-containing products. In the cake category, the products with the highest protein quality were found among gluten products, while the products with the lowest protein quality were found among gluten-free products. In the cracker category, the products with the highest and lowest protein quality are among the gluten-free products. Similarly, in the biscuit category, the products with the highest and lowest protein quality are also among the gluten-free products. As can be understood from all this, the protein quality of gluten-free products is not always inferior to that of gluten-containing products. In some product groups, they may even have higher protein quality than their gluten counterparts.

This study provides valuable insights into protein quality in gluten-free products; however, it also has some limitations. The data obtained in this study are theoretical, and the biological value and digestive properties of the ingredients used in gluten-free products may be neglected when evaluating the digestibility and amino acid profiles of foods. Furthermore, the lower PDCAAS scores of plant protein sources may not fully reflect the bioavailability of proteins in these products. Although PDCAAS is a measure developed for the general human population, it may not take into consideration that individuals on a gluten-free diet may have different digestive and microbiome characteristics. Also, although the number of products analysed as gluten and gluten-free was equal, the number of product subgroups was not; this limitation makes it difficult to compare the data. This relates to the difficulty in determining a gluten-free product group equivalent to gluten-containing products. Also, studies on the amino acid values of gluten-free products are extremely limited in the literature. Gluten-containing products have a wider range, while gluten-free products are often limited to specific types. Furthermore, the diversity of products between the two groups creates differences in terms of raw materials used, processing methods and nutritional content. Nevertheless, the study still provided important data and valuable insights into the protein quality of gluten-free products. Future studies should focus

on the amino acid profile, bioavailability, and protein combinations to enhance protein quality in gluten-free products. Furthermore, functional and sensory properties, consumer acceptance and health effects should be investigated to develop more nutritious and acceptable gluten-free products.

Conclusion

In conclusion, among the gluten-free products, those with the highest protein content were generally found in the flour category, while the pasta group had the lowest protein content. In contrast, the highest protein content was found in multigrain bread. Although the protein content of gluten-free products is not always lower than that of their gluten counterparts, their protein quality varies. According to PDCAAS analysis, the average digestibility-corrected protein quality of gluten-free products was 66.37%, while this rate was 57.44% for gluten products. The products with the highest protein quality in gluten-free products were brown rice flour bread and rice-sorghum flour bread. At the same time, the limiting amino acids were mainly lysine, sulfur amino acids (methionine+cysteine) and valine. These data suggest that gluten-free products should be evaluated in terms of both protein quality and protein content.

Compliance with Ethical Standards

Conflict of interest: The author(s) declare that they have no actual, potential, or perceived conflicts of interest related to this article.

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