NUTRITIONAL COMPOSITION OF POTATOES

AND THEIR IMPACT ON HUMAN HEALTH

Literature Review - April 2024

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Contents

A word from the author

The aim of the review is to show that potatoes are an important healthy food and to prove this with scientific studies.

This review was written during my master’s studies at the Mendel University in Brno, and my master's thesis also focused on the nutritional value of potatoes. As part of my master's thesis, I analysed the dry matter, starch, and vitamin C content of potatoes in relation to variety, tuber size, location, and year of cultivation. This was done in cooperation with the company Medipo Agras H.B., spol. s r.o.

I believe that this knowledge will help people understand that potatoes are healthy nutrient-dense, low-calorie with a high satiating effect and that potatoes are really a healthy food.

Ing. Zuzana Havlíčková

Summary

This review provides a summary of the nutritional composition and health benefits of potatoes. We demonstrate that potatoes are healthy and nutritionally balanced, high in vitamin C, antioxidants and other key vitamins and nutrients. Fibre and resistant starch make potatoes an exceptionally satiating source of low-calorie energy. Certain cooking methods, such as cooling after boiling and steaming without peeling, may further improve potatoes' health benefits.

Introduction

Potatoes are more than just a delicious and versatile side dish. As this review demonstrates, they are an exceptional course of low-calorie energy with a wide range of health benefits.

Potatoes combine several health-promoting vitamins and nutrients. Notably, they are a key source of vitamin C. One serving of boiled potatoes (150g) provides about 25% of the vitamin C RDA, making potatoes a larger contributor to world's vitamin C intake than lemons, oranges, and other seasonal fruits and vegetables. Potatoes also contain high levels of phenolic acids, carotenoids, chlorogenic acid and vitamins B6 and E – antioxidants which slow the aging process and prevent inflammation, chronic disease, cardiovascular disease, and cancer. Potassium levels in potatoes exceed even those found in foods typically associated with the essential mineral, such as bananas, avocadoes, and orange juice. They contain no fat or gluten. The quantity of protein is quite low, but the quality is very high, approaching that of egg whites.

Potatoes are an excellent source of carbohydrates, an essential source of energy. Strikingly, potatoes have a lower caloric density than all other common side dishes such as rice, pasta, or bread. This is due to their fibre, resistant starch, high water content and special dry matter composition. Fibre and resistant starch also make potatoes exceptionally satiating, a key consideration in diets and weight-loss programmes.

The exact composition of substances in a potato tuber is mainly determined by the genotype of its variety. However, it is influenced not only by environmental conditions, i.e., soil conditions, nutrient availability, altitude, and weather conditions, but also by storage conditions, cooking methods, and final processing of the product. For instance, steaming potatoes with the skin on is the best way to preserve their vitamin C content, because vitamin C is not thermostable and can leach into water upon contact. Preparing and consuming potato skins is also a good way to get the most out of potatoes' high potassium content, as this mineral is mostly concentrated in or near the skin. Cooling cooked potatoes before consumption further improves their already excellent satiating properties.

Component	Content (%)	
	Average	Range
Dry matter	23.7	13.1–36.8
Starch	17.5	8.0–29.4
Reducing sugars	0.3	0.0–5.0
Total sugars	0.5	0.05–8.0
Crude fiber	0.71	0.17–3.48
Pectic substances	—	0.2–1.5
Total nitrogen	0.32	0.11–0.74
Crude protein	2.00	0.69–4.63
Amide nitrogen	—	0.029–0.052
Amino acid nitrogen	—	0.065–0.098
Nitrates	—	0.0–0.05
Lipids	0.12	0.02–0.2
Ash	1.1	0.44–1.87
Organic acids	0.6	0.4–1.0
Ascorbic acid and dehydroascorbic acid (mg/100 g)	10–25	1–54
Glycoalkaloids (mg/100 g)	3–10	0.2–41
Phenolic compounds	—	5–30

Source: From Leszczynski, W., in: *Potato Science and Technology*, Lisinska, G. and Leszczynski, W., Eds., Elsevier Science Publishing Co., Inc., New York, 1989, pp. 11–128.

Figure 1: Chemical composition of potato.

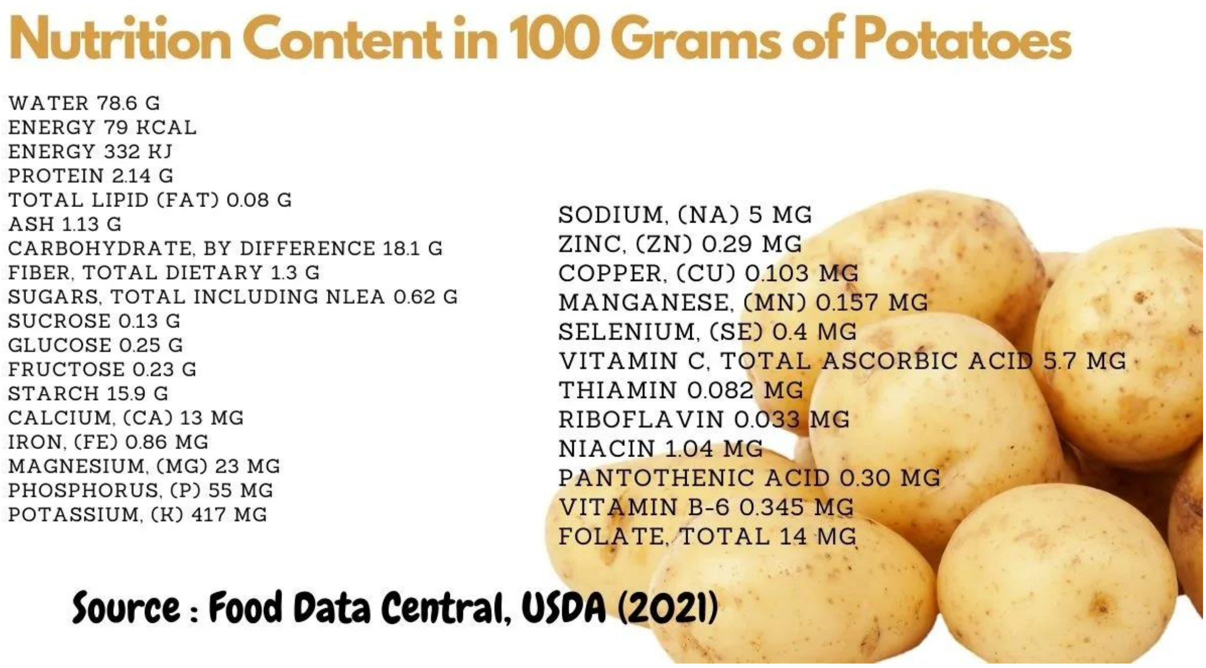

Figure 2: Chemical composition of potato.

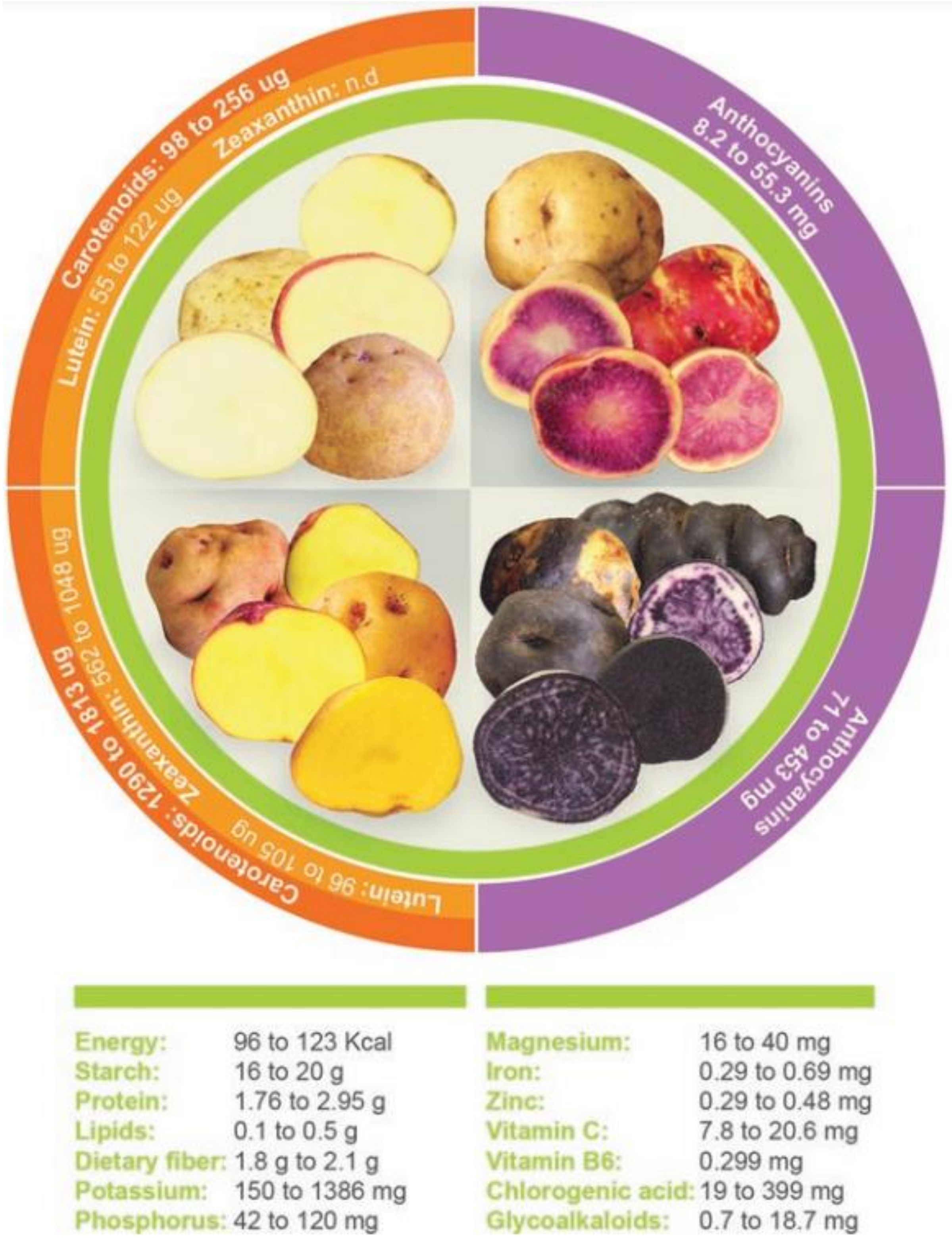

Figure 3: Chemical composition of 100 g fresh potatoes (Burgos et al., 2020).

PART 1: NUTRITIONAL COMPOSITION OF POTATO

Energy

Potatoes have a low energy density due to their high content of water (80 %) and specific dry matter composition. The energy content is low because of content of dietary fibre and resistant starch, which are resistant to digestion. Resistant starch content increases after cooling of boiled potatoes, because of starch molecules retrogradation. Boiled potatoes have lower energy than pasta and rice and it is the most satiating side dish (Holt et al., 1995). Therefore potato is more satiating food than pasta and rice, which decreases the amount of food eaten, and thus potatoes help to maintain the weight (Zhang et al., 2018).

The energy content of potatoes is strongly influenced by the cooking method. 100 g of boiled potatoes contain 86 kcal, baked potatoes 109 kcal while French fries 564 kcal and potato crisps 564 kcal (Beals, 2019; Burgos et al., 2020). Boiled rice contains 137 kcal, boiled pasta 141 kcal, bread 276 kcal, so boiled potato has the lowest caloric density from the most common side dishes (Gebhardt and Thomas, 2002).

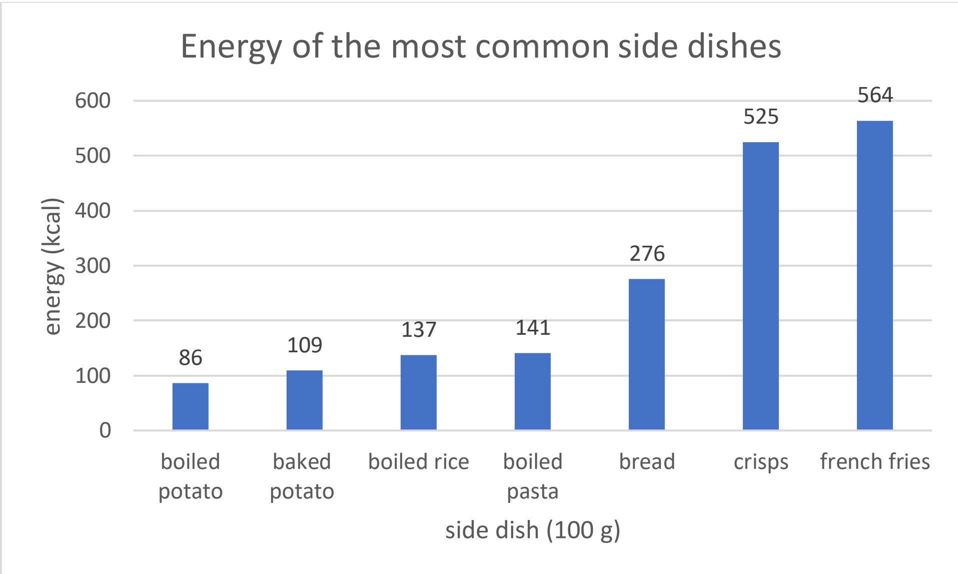

Figure 4: Energy of the most common side dishes (per 100 g)

Dry matter

The quality of the potato tuber is mainly influenced by the dry matter content (Brown, 2005). According to IPC (International Potato Center) the dry matter content of potato ranges from 13,7 to 34,8 %, usually 15 – 25 % and the remainder of the tuber being water. The dry matter content in vegetables is in the range 4-25 %, which corresponds to the classification potato as vegetable. The botanical definition of a vegetable is: "Botanically, a vegetable is anything that is not the reproductive portion of the plant derived from a flower. A root or tuber such as for yam or potato are vegetables" (Russo, 2021).

Dry matter content is determined by the variety, but it is also influenced by climatic conditions, length of vegetation, soil type and effect of pests and diseases (Woolfe 2009). As mentioned above the main influence on dry matter is variety. There is a strong influence of processing or cooking type. The lowest dry matter is reached in very early potatoes, due to their genotype and short vegetation and usually harvesting before it is physiologically mature (Bárta et al. 2008). Soft potatoes have lower dry matter than firm potatoes. Potato varieties suitable for starch production which usually have a very long vegetation period have the highest dry matter.

From the growing point of view dry matter content is influenced by light (length of day and night), which directly affects foliage growth and stimulates photosynthesis and respiration (Zhou et al., 2017). The length of day and night influences tuberization and flowering. Lower temperatures are preferred for dry matter production (the optimum is around 14-20 ^{0}C), because if they are higher, a greater proportion of sugars are consumed for respiration, reducing the efficiency of dry matter utilization. Too high temperatures can also delay the initiation of tuberization, thereby reducing the time for starch deposition in tubers (Zhou et al., 2017).

Higher altitude and cold weather conditions with higher precipitation lead to lower dry matter than in hotter and drier weather at lower altitude (Vokál et al. 2000). The comparison of different years with different weather conditions confirmed this, but not significantly (Escuredo et al. 2018). Hamouz et al. (2005) compared differences between higher and lower altitudes in the Czech Republic and confirmed this trend, but not significantly. Bárta et al. (2008) found that irrigated potatoes had significantly lower dry matter than non-irrigated potatoes. Sawicka and Pszczółkowski (2005) state that potato dry matter is the highest under low rainfall conditions. There is also a highly significant negative correlation between the rainfall 10 days before harvest and the dry matter (Zgorska and Frydecka–Mazurczyk 2000). Zarzecka et al. (2021) state that there is also important even distribution of rainfall, which contributes to higher dry matter.

Dry matter is influenced by fertilisation, the highest dry matter was achieved when the nitrogen dose was 125 – 200 kg/ha N (Zhou et al. (2017) Sommerfeldt and Knutson (1968), Darwish et al. (2006)), because too high dose of nitrogen supports foliage growth instead of tuber growth, but the most important is a balanced nutrition also with other nutrients.

There is an increase in dry matter after most of the cooking method except cooking in the water, which decreases the dry matter content (Narwojsz et al., 2020).

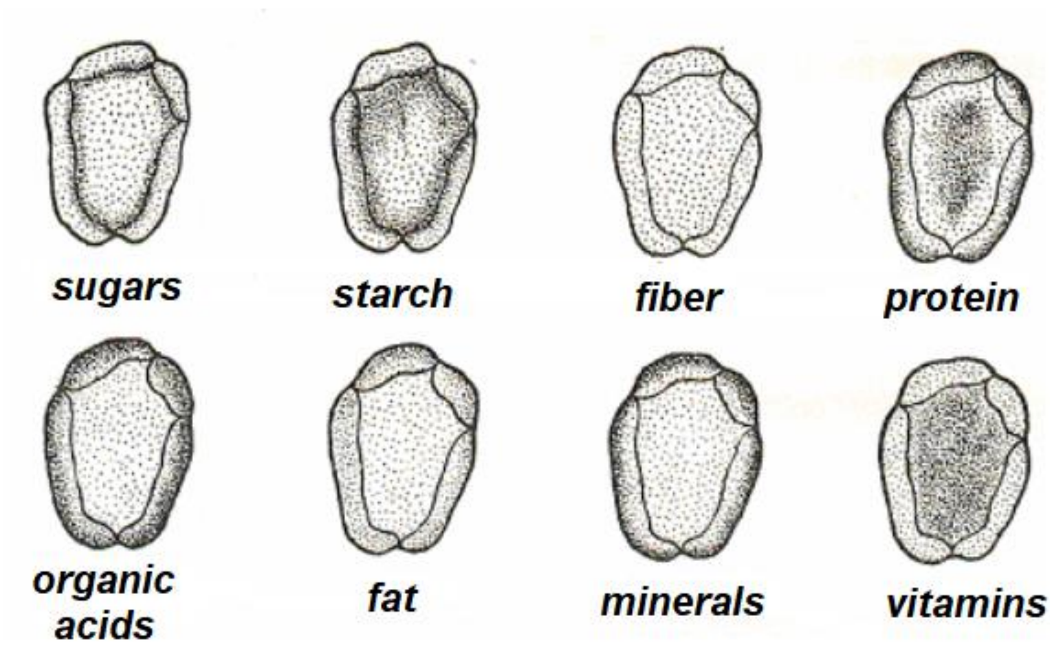

Figure 5: Distribution of nutrients in potato tuber (Rybáček, 1988).

Minerals

Mineral	*Content (mg/100 g fresh potato)*	*% RDA*
Potassium	450,0	15
Calcium	10,0	1
Phosphorus	78,0	6
Copper	0,1	7
Manganese	0,1	7
Magnesium	22,0	5
Iron	0,5	4
Zinc	0,5	2
Selenium	0,5	1

Figure 6: Content of main minerals in 100 g fresh potato and the percentage of RDA. Resource: www.vubhb.cz

Minerals have many important functions in the potato plant, such as structural, energetic, or osmotic and they are also components of various enzymes. The need of potato plant is influenced by many factors, such as weather conditions, soil type, nutrient content in the soil, location, timing and the dose of fertilisation and the requirements of the variety. Maximum yield can be achieved through optimal and balanced nutrition (van Eck, 2007). An increase in the mineral element supplied to the plant in fertilisers leads to an increase in the content of this element in the potato plant and tubers. However, the uptake of elements by plants is mutually influenced by the ratio of elements in the soil, but also by the distribution of elements in the plant body (White et al., 2009).

The utilisation of minerals in human body from potatoes is relatively high because they contain high level of vitamin C, which increases the utilisation of minerals (especially iron and zinc). Bioavailability is also increased because of low levels of phytic acid and oxalates (which reduce mineral bioavailability in many other crops) (White et al., 2009).

Mineral content is higher in the skin and near the skin than in the flesh (Bošković-Rakočević et al., 2018; Rybáček, 1988).

Potassium is the most abundant mineral in potato, as it contains about 400 mg/100 g FW according to USDA but it can vary between 150 and 1386 mg/100 g FW (Nassar et al., 2012). According to NIH (National Institutes of Health, USA), the recommended daily intake of potassium 4 700 mg per capita and 100 g of boiled potatoes contributes up to 16 % of the recommended daily intake. Since most of the potassium is in the skin and near the skin, the best way to preserve as much potassium as possible in potatoes is to boil or bake them with skin. Boiling diced or shredded potatoes reduces potassium levels by 50 % and 75 %, respectively. (Bethke and Jansky, 2008). Potassium helps control blood pressure, and it can reduce the risk of stroke.

Potatoes contain much more potassium than other side dishes (Figure 7). Potatoes (baked with skin) even contain more potassium (544 mg/100 g) than foods associated with high potassium levels such as bananas (358 mg/100 g), orange juice (200 mg/100 g) and avocado (485 mg/100 g) (Dietary Guidelines Advisory Committee, 2015).

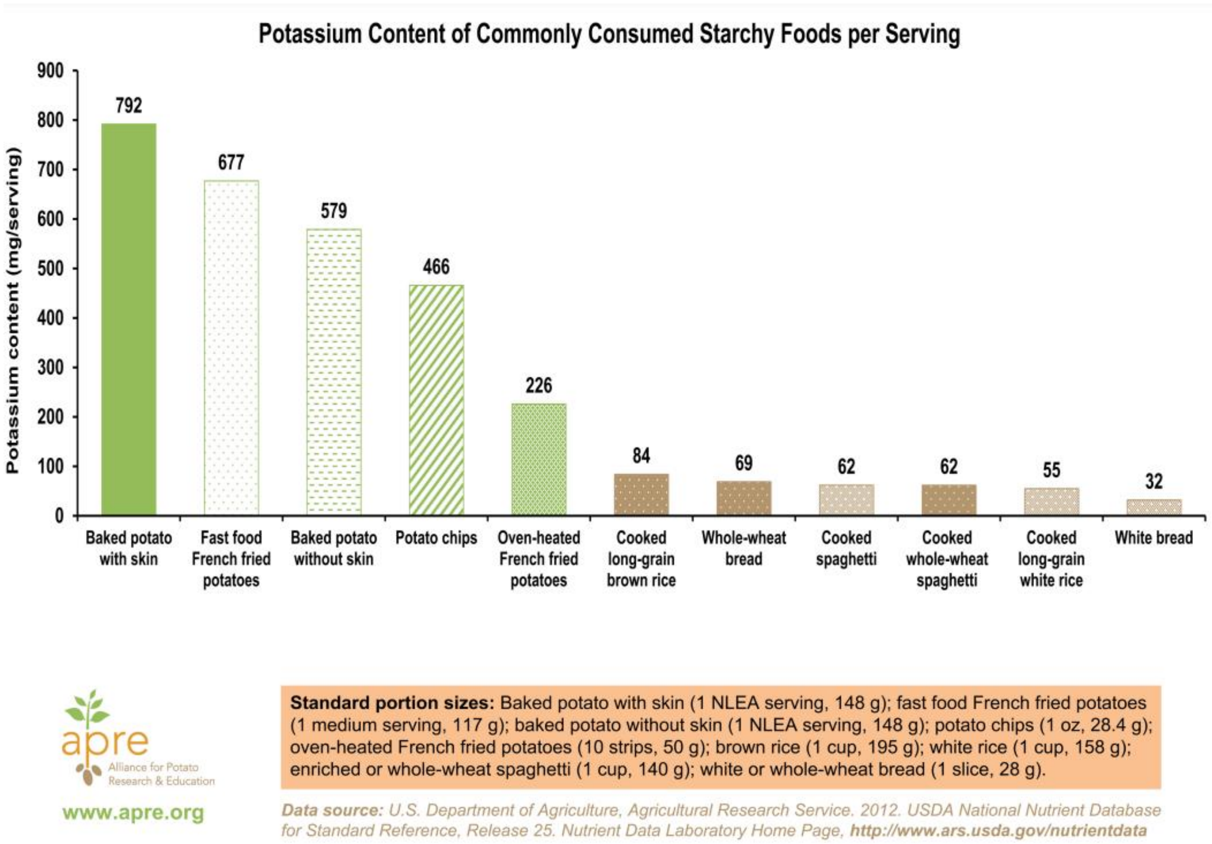

Figure 7: Potassium content of commonly consumed starchy foods per serving. source: www.apre.org

There is also moderate content of magnesium (14-18 mg/100 g) and phosphorus (30-60 mg/100 g) contributing 5 and 6 % of RDA, respectively, and there is small amount of calcium (5-18 mg/100 g) contributing only 1 % of RDA (Burgos et al., 2020).

The iron and zinc content is quite low (0,29 - 0,69 mg/100 g FW and 0,29-0,48 mg/100 g FW respectively), but the utilisation of these minerals in the human body from potatoes is relatively high because they contain high level of vitamin C, which increases the bioavailability and low level of phytic acid and oxalates, which decrease the bioavailability of minerals. (White et al., 2009).

Selenium is an important antioxidant that reduces the action of reactive oxygen species, has a positive effect on thyroid function, the vascular system, and prevents cancer and other civilisation diseases (Cuderman et al., 2008; Poggi et al., 2000; Rayman, 2012). The recommended daily intake of selenium is 55 µg (Monsen, 2000) to 70 µg (Camire et al., 2009), and a dose higher than 400 µg of selenium per day is considered risky (Monsen, 2000). Potatoes contain 1 µg/100 g FW of selenium (Lachman and Hamouz, 2005; Vreugdenhil and Bradshaw, 2007). Considering a 150g portion of potatoes contains 1,5 µg of selenium, this covers 2-3% of the selenium RDA. Selenium is mostly deficient in the human diet, and therefore potatoes could be enriched with selenium, as they can accumulate this element quite well in tubers, when supplied with selenium fertilisers (Barta et al. 2008). The most effective incorporation of selenite or selenate occurred during foliar application at the tuberization stage, when the selenium content reached 0,95-1,5 mg/kg DW (Zhang et al. 2019).

Carbohydrates

Starch

Potatoes usually contain 15-20 % starch in fresh weight, it can range from 11,0 to 30,4 % with an average of 18,8 % (Singh and Kaur, 2016). Approximately 70 % of the dry matter is starch (Lu et al., 2011). The starch content is influenced by genotype and maturity, as late varieties contain usually more starch and very early varieties are low in starch (van Eck, 2007). Too high dose of nitrogen fertilizer reduces the starch content (Hajšlová et al., 2005; Vokál, 2013).

Starch is composed of amylopectin and amylose in a relatively stable ratio 3:1 (Akyıldız et al., 2015; Woolfe, 1987). Amylopectin is a highly branched polysaccharide made up of about 10^5 glucoses, while amylose is linear molecule composed of about 5 000 glucoses. The ratio of amylopectin to amylose affects properties of the starch product the most. Potato starch is specific with big starch grains, almost no fat and high phosphorylation, which also affluence the final starch product (Liu et al., 2007).

From digestive point of view, starch is divided into rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS). RDS is digested in the small intestine within 20 minutes, SDS is also digested in small intestine within 20 – 120 minutes, and RS is not digested, and it reaches the large intestine, where it is fermented by microbes. RDS and SDS consist mainly of amylopectin and have a higher glycaemic index and RS consists mainly of amylose and helps maintain gut health. The starch in raw potatoes is substantially resistant to amylolytic enzymes so it acts like resistant starch (RS) (Camire et al., 2009).

After cooking (at 70 ^{0}C), starch gelatinises, making it more accessible to amylolytic enzymes. Amylopectin with a highly branched structure is easier to digest than linear amylose, so amylopectin has higher response for glycaemic index of potato. Part of the starch (more amylose) is also resistant to digestion in the small intestine after cooking and it behaves like fibre and has also similar health benefits in the gut. After cooking and cooling, potatoes high in amylose-starches have greater retrogradation which results in more crystalline structure and resistance to digestion (amylopectin is digested easily, because the retrogradation is less common). Potatoes contain 68 % RDS, 3 % SDS and 3,9 % RS immediately after cooking, but 44 % RDS, 23 % SDS and 7 % RS after cooling cooked potatoes (Monro et al., 2009). Thus, cooked and cooled potatoes have a higher RS content than cooked hot potatoes, and thus improve the gut health like fibre and have lower glycaemic effect. Raatz et al. (2016) found significant differences between cooking methods and RS content, with the highest RS found in cooled (boiled or baked) potatoes (4,3 %). Reheated potatoes (3,5 %) and baked potatoes had more RS (3,6 %) than hot boiled potatoes (2,4 %) (Camire et al., 2009; Šimková et al., 2013).

Non-starch carbohydrates

The main non-starch carbohydrates in potatoes are fibre, reducing sugars – monosaccharides (glucose and fructose) and disaccharide (sucrose). Low temperatures cause that part of the starch breaks down into sugars, which can cause problems with darkening during frying and acrylamide formation (Cottrell et al., 1995).

Fibre is not digested and is not absorbed in small intestine, but it can be fermented in the large intestine. It helps maintain the gut health and promotes “good” microbes in large intestine. Cooked potatoes with skin contain more fibre (2,1 g/100 g) than cooked potatoes without skin (1,8 g/100 g), which is more than white rice (0,3 g/100 g), but potatoes are not considered as high-fibre food, the best sources are whole grain cereals (10-17 g/100 g), while the RDA for fibre is 20-35 g (Dhingra et al., 2012).

Protein

Potato protein content is 1,7-2,1 g/100 g FW (Vreugdenhil and Bradshaw, 2007) and about 10 g/100 g DM (range of 8,7 - 14,2g/100 g) (Lu et al., 2011), which is quite low, but the amino acid composition has an exceptionally very high biological value (90-100), which is similar to the whole egg standard (100), and higher than cow's milk (84-88), beef (83-92) or beans (73) (Vreugdenhil and Bradshaw, 2007). Potato protein contains high levels of all nine essential amino acids (including lysine which is usually low in plant sources such as rice or pasta), but low in sulphur amino acids (Camire et al., 2009; Woolfe, 1987). The main proteins contained in potatoes are patatin (patatin can be an allergen for some people, but it is well reduced by cooking) and a group of inhibitors of proteases (Camire et al., 2009). The contribution of protein intake from potato can be higher than intake from legumes, which have a high protein content, but are not eaten in such a large quantities (Bárta et al., 2008).

Potato protein content is mainly influenced by variety, growing conditions, and fertilisation. Growing potatoes at higher altitude increases protein content. Since proteins are 16 percent nitrogen, the nitrogen fertilisers have a significant effect on protein content (Bártová et al., 2009).

Potato protein content is also influenced by the cooking method. Raw potatoes contain 2 g/100 g FW, boiled potatoes 1,8 g/100 g FW and baked potatoes 2,2 g/100 g FW (Vreugdenhil and Bradshaw, 2007).

According to Pęksa et al. (2018), the protein content decreases during storage (6,4 % after 3 months and 19 % after 6 months).

Potatoes have a similar protein content (2 g/100 g) as other vegetables and fruits, with the exception of legumes and beans with 5-8 g/100 g of protein (Gebhardt and Thomas, 2002).

Fat

Potatoes are low in fat and low in calories compared to other common side dishes. Boiled or baked potatoes contain only 0,1 g of fat/100 g FW, which is less than boiled pasta (0,5 g/100 g FW) and boiled rice (1,95 g/100 g FW) (Priestley, 2006). The fat content increases rapidly after frying, so that fried potato products such as crisps and French fries contain 36 g/100 g and 19 g/100 g of fat respectively (Gebhardt and Thomas, 2002).

Most of the lipids in potatoes are structural elements of biological membranes (phospholipids, glycols and galactolipids) and neutral lipids (acylglycerols and free fatty acids) (Ramadan and Oraby, 2016).

Table 1.15 Nutritional values of potatoes, rice and pasta – based on new potatoes boiled in skins, boiled white rice, and cooked penne pasta [with permission of British Potato Council (BPC, 2004b), Market Information and Statistics].

	Potatoes (175 g)	**Pasta (230 g)**	**Rice (180 g)**
Price per portion	17 p	20 p	21 p
Energy value	126 kcal	198 kcal	248 kcal
Carbohydrate	27 g	43 g	56 g
Fat	0.17 g	1.15 g	2.99 g
Protein	3.15 g	6.9 g	4.68 g
Fibre	2.1 g	2.07 g	0.18 g
Vitamin C	0.5 mg	None	None
Vitamin B6	0.58 mg	0.023 mg	0.13 mg
Folate	45.5 µg	6.9 µg	7.2 µg

Figure 8: nutritional values of potatoes, rice and pasta (all boiled)(Vreugdenhil and Bradshaw, 2007).

Vitamin C

Vitamin C (ascorbic acid) is the most abundant vitamin in potatoes. It is an important antioxidant and free radical scavenger of reactive oxygen species, which may contribute to degenerative diseases such as heart disease and cancer. Vitamin C also increases the bioavailability of iron from food and is important for collagen formation. Vitamin C deficiency leads to disease called scurvy, which causes fatigue, increased susceptibility to bruising and bleeding, joint swelling and loss of hair and teeth. It is an essential nutrient, because the human body cannot synthesise it itself, so it must be obtained from food. (Love and Pavek, 2008).

According to Food and Nutrition Information Center (USA) the RDA for vitamin C is 90 mg for males, 75 mg for females. There is an increased need for pregnant females (85 mg), breastfeeding women (120 mg) and smokers (+ 35 mg compared to non-smokers). Potatoes contain vitamin C in range 8-21 mg/100 g FW (Burgos et al., 2020). If we consider average 13 mg vitamin C in 100 g of boiled potatoes, so 150g portion with 20 mg of vitamin C covers 22-26 % of RDA (Gebhardt and Thomas, 2002).

There is an essential affluence of vitamin C by potato variety and its genotype, but there are many factors that influence it, such as cooking method, growing conditions, and storage. It was found that the genotype and the flesh colour affluence vitamin C content (Külen et al., 2013; Lachman et al., 2013; Valcarcel et al., 2015). Dark yellow flesh potatoes usually have a higher vitamin C content than white flesh potatoes and the average of red and blue flesh potatoes (D'Amelia et al., 2022; Lachman et al., 2013). On the other hand absolutely highest vitamin C content was found in Rosemarie with red flesh followed by Agria (yellow flesh) (Hamouz et al., 2018a).

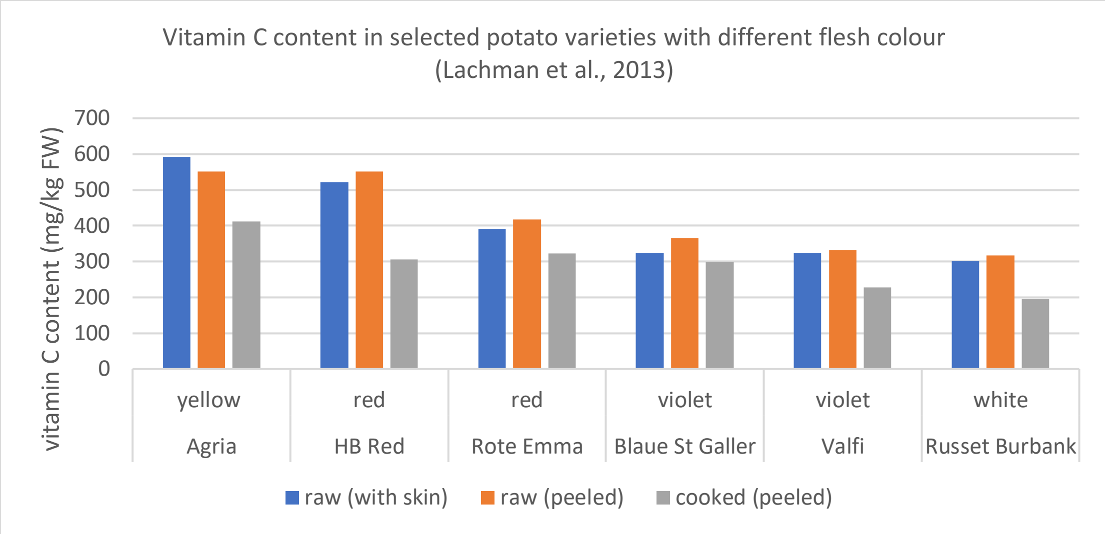

Figure 9: Vitamin C content in selected varieties with different flesh colour (yellow, red, violet, white) raw and after cooking (Lachman et al., 2013).

Raw potatoes contain 16-33 mg/100 g FW with an average of 24 mg/100 g FW of vitamin C (Akyıldız et al., 2015). There is a significant reduction in vitamin C after cooking (Lachman et al., 2013). The best way to keep as much vitamin C as possible is to cook it with skin, to cook in minimum of water (where it can be leached out) and to reduce the cooking time. Steaming with the skin results in the least loss of vitamin C (Love and Pavek, 2008). Augustin et al. (1978) state that raw potatoes contain 14,3 mg/100 g, cooked with skin 12,3 mg/100 g, cooked peeled 10,9 mg/100 g, baked 11,7 mg/100 g and microwaved 12,6 mg/100 g. Lachman et al. (2013) state that vitamin C content is reduced to 69 % after cooking, to 67% after microwaving and to 37 % after baking. In table below see the data from Love and Pavek (2008), cooking non-peeled potatoes is the most thrifty to vitamin C with a reduction to a maximum of 21 % of raw potatoes, similarly 20 % loss of vitamin C after boiling was found by Öhrvik et al. (2010). Fang et al. (2022) found that steaming and microwaving were the best cooking methods to maintain as much as possible of vitamin C. Surprisingly there is also about 50 % of vitamin C is retained in potatoes after frying, so fried potatoes are also a source of vitamin C.

Most of vitamin C in potatoes is in the flesh, but it is better to keep the skin on potatoes during cooking because the skin protects the vitamin C from leaching into water and heat destruction (D'Amelia et al., 2022; Lachman et al., 2013).

Cooking method	**Loss of vitamin C (%)**
Baked	15-28
Microwaved	12-27
Cooked in skin	16-21
Cooked peeled	23-34
Fried	15-49
Pre-fried	41-55
Mashed potatoes	20-67
Dehydrated	50-81

Figure 10: Loss of vitamin C after different cooking methods (Love and Pavek, 2008).

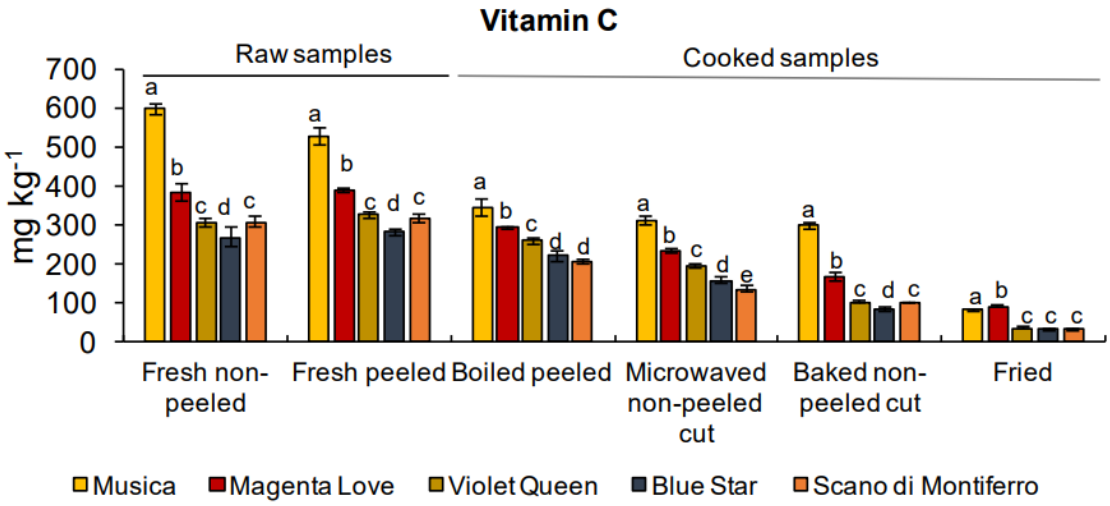

Figure 11: Effect of variety, cooking methods (boiled, microwaved, baked, fried) and peeling on vitamin C content (mg/kg). Means denoted by the same letter, within the same group described on the x axis, did not differ significantly at p ≤ 0,05 according to Tukey's multiple range test (D'Amelia et al., 2022).

Content of vitamin C is influenced by growing conditions, because of stress conditions usually increase the content of antioxidants, including vitamin C. Potatoes from warmer and drier areas have higher vitamin C content than those from colder and wetter areas (Hamouz et al., 2018a). There is also a strong influence of the weather and thus of the growing season. A lot of rainfall decreases vitamin C content, especially before harvest. On the other hand, the uneven rainfall probably increases vitamin C content (Valcarcel et al., 2015). Sandy soils increase vitamin C content compared to heavy clay soils (Valcarcel et al., 2015).

Vitamin C content decreases during storage. Potatoes contain most of the vitamin C immediately after harvest. Vitamin C content decreases the most after 2-3 months of storage and then it remains at a stable level (Shekhar et al., 1978). Külen et al. (2013) found that the vitamin C content decreased by 24 % after 2 months of storage, by 45 % after 4 months and by 52 % after 7 months. In the experiment of Hamouz et al. (2018), the vitamin C content decreased by 53,4 % after 6 months. Hajšlová et al. (2005) also found similar results, the vitamin C content decreased by 39-48 % after 5 months.

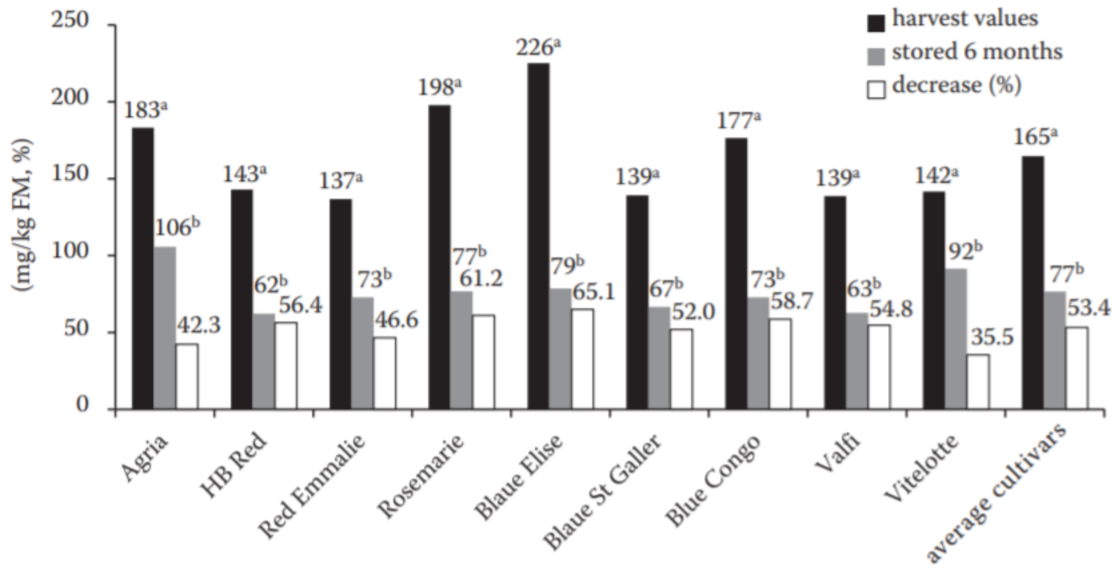

Figure 12: Effect of storage (4 °C) on vitamin C content in potato tubers (Hamouz et al., 2018a).

Potatoes aren't as high in vitamin C as lemons, oranges, or peppers, but because they are eaten all year round, potatoes contribute about 20 % of all vitamin C intakes. This is much more than even lemons or peppers do. As Storey and Davis (1992) state that 15 - 20 % of vitamin C intake comes from potatoes, which is more than from any other vegetable or fruit. Górska-Warsewicz et al. (2021) also found that potatoes provided 14 % of daily intake of vitamin C in Poland, which is more than from any other food. Increasing the vitamin C content of potatoes, would have a high potential to improve health worldwide.

There are three ways how to increase the vitamin C intake according to Love and Pavek (2008):

1) Improve the diet – increase the intake of foods rich in vitamin C content such as potatoes.
2) Improve the crop –vitamin C content can be increased by breeding, as the gene for vitamin C content is highly heritable (but it is not priority of breeding to increase vitamin C content), and by growing conditions.
3) Cooking methods – there is always some reduction in vitamin C content when cooking, so it is recommended to use the thriftiest cooking method such as steaming with skin.

Vitamin B6

Vitamin B6 (pyridoxine) is one of B-complex vitamins. This vitamin consists of 3 compounds (pyridoxol, pyridoxal and pyridoxamine). The B-complex of vitamins is important for many metabolic functions and nervous system, synthesis of neurotransmitters (dopamine and serotonin) in human body. In the plant body it is important as an antioxidant to prevent pathogen attack (Burgos et al., 2020).

According to FDA, the RDA for vitamin B6 is 1,7 mg, while the Institute of Medicine (1998) states that the RDA of vitamin B6 is 1,3 mg. Potatoes contain 0,3 mg/100 g FW of vitamin B6, so just 100 g of potatoes can contribute by 18-23 % to the RDA. Górska-Warsewicz et al. (2021) found that in Poland, potatoes provide 15 % of the daily intake of vitamin B6, which is more than any other vegetable. Compared to other side dishes, the vitamin B6 content in 100 g of rice is 0,050 mg, maize 0,139 mg and wheat 0,034 mg (Fudge et al., 2017).

Vitamin B6 content is influenced by genotype of variety, but not by flesh colour (Mooney et al., 2013).

Cooking has little effect on the vitamin B6 content. There were found following vitamin B6 contents in 150 g FW: raw 0,33 mg, cooked with skin 0,35 mg, cooked without skin 0,29 mg, baked 0,38 mg, microwaved 0,39 mg (Augustin et al., 1978). Robertson et al. (2018) also found minimal differences between raw potatoes and potatoes after different cooking methods.

During the storage (6,7 and 8,9 ^{0}C) the vitamin B6 content has increased after 227 days at both storage temperatures, but the increase was higher at 8,9 ^{0}C, by 23-42 % (Mooney et al., 2013). Goyer et al. (2019) found an increase of vitamin B6 during storage by 5-24 % after 8 months storage at 7,8 ^{0}C. Öhrvik et al. (2010) also found increase of vitamin B6 by 20 % after 6 months. The increase is probably due to the new synthesis of pyridoxine glycoside (pyridoxal and pyridoxamine remained at the same level) (Addo and Augustin, 1988).

Vitamin E

Vitamin E (mostly abundant in potatoes as α-tocopherol) is a fat- soluble vitamin produced only by photosynthetic organisms and is considered a powerful antioxidant essential for human health and has a preventive effects against chronic diseases (Andre et al., 2010), cancer, arthritis, atherosclerosis, cataract and signs of ageing (Crowell et al., 2008; Rizvi et al., 2014).

While the RDA for vitamin E is 15 mg, potatoes contain only 0,05 – 0,28 mg/100 g FW of α-tocopherol (Lachman and Hamouz, 2005). While commercial varieties contain 0,015 – 0,075 mg/100 g FW of vitamin E, the wild potato species contain 0,068 – 0,517 mg/100 g, so the content can be improved by breeding using the wild species or by genetic manipulation (Andre et al., 2007). There is also a correlation between vitamin E content and carotenoid content in potatoes, so improving one will improve both of these compounds in potatoes (Upadhyaya et al., 2021).

There is evidence that stress factors (draught, high radiation) increase the content of antioxidants including vitamin E (Andre et al., 2009; Lushchak and Semchuk, 2012).

During cooking, the vitamin E content in potatoes is only slightly reduced (Piironen et al., 1987), but during frying (respectively adding the oil) the content of vitamin E can be increased (up to 4,9 mg α-tocopherol/100 g), because oils are important sources of vitamin E, but the content of the final product depends on the length of frying, the type of oil and the number of frying cycles (Fillion and Henry, 1998; Robertson et al., 2018). On the other hand Andrikopoulos et al. (2002) found that vitamin E content decreased even after frying (decrease by 20 % after frying in new oil, by 50 % after 2-3 frying cycles).

An increase in vitamin E was found in potatoes during storage, regardless of storage temperature (3 and 9 ^{o}C), but there were differences between the varieties. On average, the vitamin E content increased fourfold after 40 weeks of storage (Spychalla and Desborough, 1990).

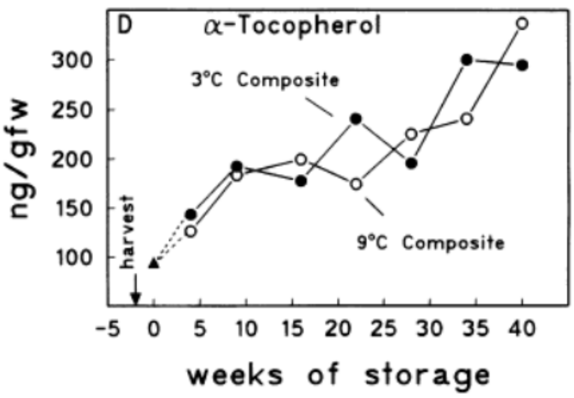

Figure 13: Vitamin E (α-tocopherol) content in potatoes related to weeks of storage and storage temperature (Spychalla and Desborough, 1990).

Phenolic compounds

Phenolic compounds (polyphenols, phenolics) are the most abundant and diverse group of antioxidant substances in plant foods and are therefore gaining increasing attention in a healthy diet. They are thought to have antibacterial, hypoglycaemic, antiviral, anticancer, anti-inflammatory, and vasodilatory properties. In potatoes, polyphenols make up 90 % of all antioxidants. Plants produce polyphenols to protect themselves from attack by bacteria, viruses, and fungi. In the plant body, they are found in vacuoles or stored in cell walls (Burgos et al., 2020).

Potatoes contain 122,6 – 440,5 mg/100 g FW of phenolics (Lachman et al., 2005) and the content is influenced by genotype of variety, flesh colour, growing conditions (year, locality, fertilisation) (Hamouz et al., 2010). Potato peels contain more than 50 % of phenolics, making it an important source of phenolics (Akyol et al., 2016; Wu et al., 2012).

Varieties with red or blue flesh have higher total phenolic content (TPC). The blue flesh variety Valfi has 2,46 – 3,18 times higher TPC (13,29 mg/g DM) than eight yellow flesh varieties (4,18 - 5,39 mg/g DM) (Hamouz et al., 2010). Similar results were found by Külen et al. (2013), the average of nine colour flesh potato varieties (red or blue) has 10,3 mg/g DM TPC and the average of white or yellow flesh potatoes has 4 mg/g DM TPC. Comparing colour flesh potatoes, the highest TPC is found in dark flesh potatoes (Violette 25,8 mg/g DM, Vitelotte 25,9 mg/g DM) and the lowest in coloured flesh only around vascular bundles (Shetland Black 19,4 mg/g DM) (Hamouz et al., 2010).

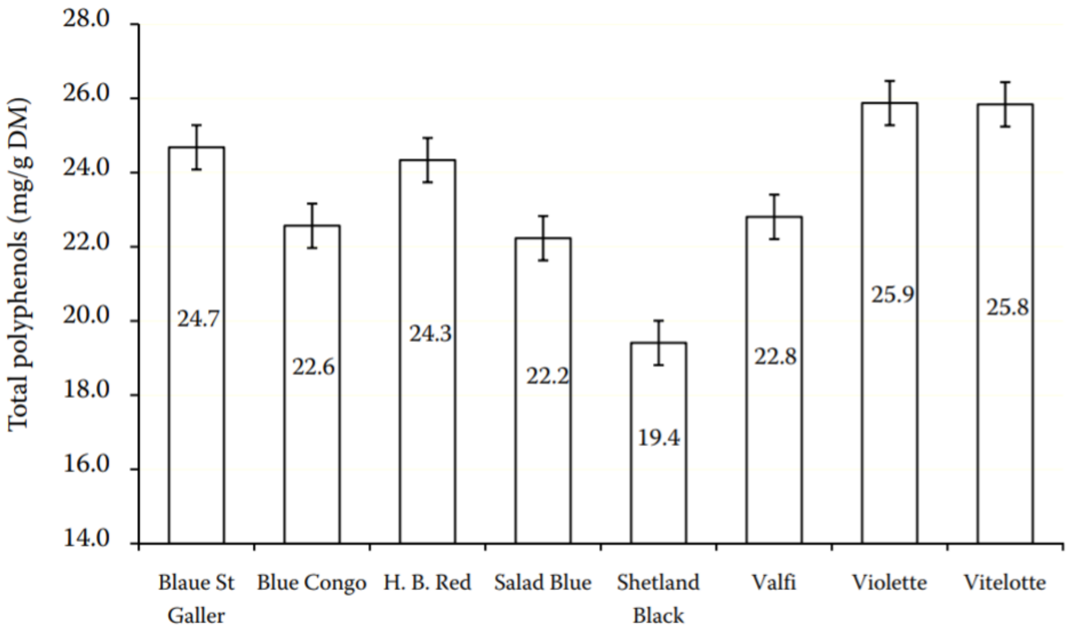

Figure 14: Averege TPC of 8 potato varieties with red and purple flesh from localities in The Czech Republic (Stachy and Valečov) in year 2008 (Hamouz et al., 2010).

Extreme weather conditions and stress increase phenolics content. Dry year with low precipitation results in high phenolics content (3,6 g/kg DM, compared to 3,28 and 2,81 g/kg DM in normal year) (Keutgen et al., 2019). Hamouz et al. (2010) found that the warm and dry locality at low altitude Přerov nad Labem and the very cold and wet locality at high altitude Stachy have higher phenolics content.

Külen et al. (2013) found that in varieties with coloured flesh, the value of total phenolic compounds decreased significantly after 2 months of storage and then gradually increased, and after 7 months of storage, the value of total phenolic compounds was at the values measured immediately after harvest (in varieties with white and yellow flesh, these changes were not significant, but the same trend was observed). Blessington et al. (2010) reported that the total phenolic content was higher in tubers immediately after harvest than in tubers after 4 months of storage at 4 ^{0}C or 20 ^{0}C, but when stored at 4 ^{0}C and then reconditioned at 20 ^{0}C, the phenolic content was the same or even higher than immediately after harvest.

Cooking methods appear to influence phenolic content in potatoes, but there are many different results in research. Boiled potatoes contain less phenolics than baked potatoes (Narwojsz et al., 2020), partly due to leaching into water and partly due to oxidation (Jayanty et al., 2019). Some of the research found that baking (348.46 mg/100 g DM) and cooking (210.96 mg/100 g DM) resulted in higher phenolic content (Narwojsz et al., 2020). Blessington et al. (2010) also reported a higher level of total phenolic compounds in baked, fried or microwaved potatoes compared to raw potatoes. Some studies found the opposite result, that boiling, baking and microwaving decreased the phenolic content found in raw potatoes, while the losses where smallest in boiled potatoes (Perla et al., 2012; Xu et al., 2009). So, more research is needed in this topic.

There are 4 most important groups of phenolics in potatoes:

A) Chlorogenic Acid
B) Flavonoids – anthocyanins
C) Carotenoids
D) L-tyrosine

Chlorogenic Acid

Chlorogenic acid accounts for about 80% (Brown 2005) - 90 % (Fang et al., 2022) of the total phenolic content in whole potatoes and 90 % of chlorogenic acid is in potato peel (Schieber and Saldaña, 2009). Chlorogenic acid content is in correlation with total polyphenol content (Hamouz et al., 2010). Chlorogenic acid content increases after pathogen invasion and its main function is to protect against pathogen action (Yogendra et al., 2014). Its benefit to human health is due to its antioxidant properties, as chlorogenic acid is able to scavenge reactive oxygen species and thus acts as a preventive agent against the development of a wide range of degenerative chronic diseases and ageing (Burgos et al., 2020).

Variety and growing conditions have the greatest influence on the variability of chlorogenic acid content. Variety has a significant effect on chlorogenic acid content (Hamouz et al., 2010). However, Keutgen et al. (2019) did not find significant differences between studied varieties (for the ten varieties and clones studied). It was found that potatoes with red or violet flesh have 5 – 7,6 times higher chlorogenic acid content than potatoes with yellow flesh colour (Lachman et al., 2013) This is also confirmed by Orsák et al. (2019), who found that yellow flesh potatoes have significantly lower chlorogenic acid content than red and purple flesh potatoes, while purple potatoes have insignificantly higher content than red ones.

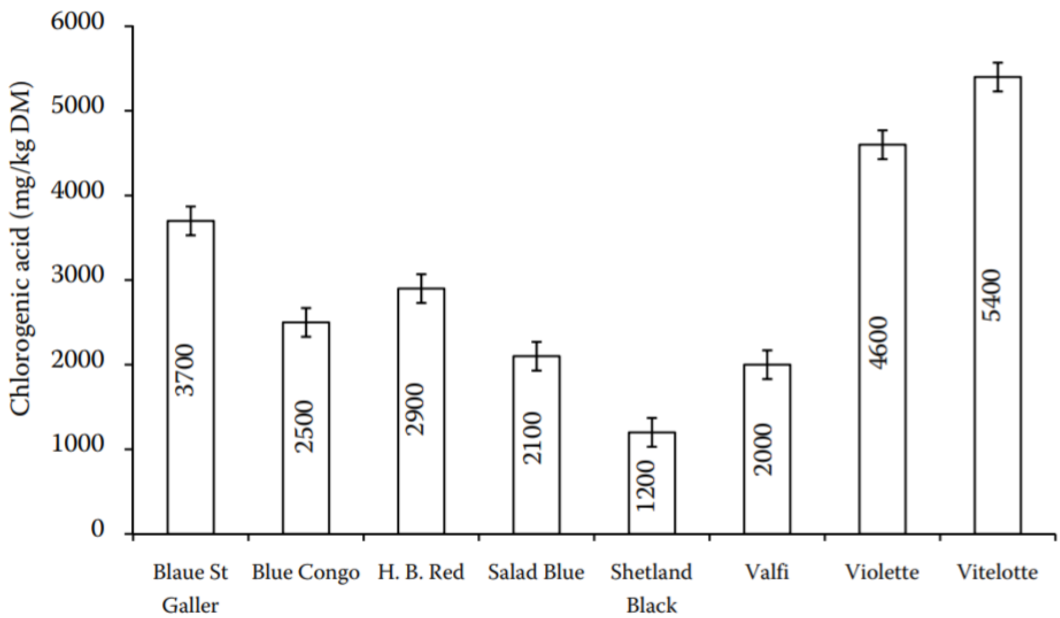

Figure 15: Average content of chlorogenic acid in 8 varieties from 2 localities (Stachy and Valečov) in 2008 (Hamouz et al., 2010).

Organic potatoes were found to have higher level of chlorogenic acid than conventionally grown potatoes. In six of eight varieties studied at both locations and in all four years studied, statistically significant higher levels of chlorogenic acid were observed in varieties grown under organic farming compared to conventional farming (Hajšlová et al., 2005). Year of growing significantly influence chlorogenic acid content, in 2015, which was the driest year, the chlorogenic acid content was higher (2,29 g/kg DM) than in wetter years, in 2014 it was 1,2 g/kg DM and in 2016 it was 0,6 g/kg DM (Keutgen et al., 2019).

After 6 months of cold storage (4 ^{o}C), there was an average increase of 87,5 % in chlorogenic acid in colour-fleshed potatoes, while the yellow-fleshed variety Agria increased only by 4,3 % compared to the post-harvest content (Orsák et al., 2019). The increase of 50-430 % after 90 days was also observed by Yamdeu Galani et al. (2017).

Cooking methods lead to a decrease in chlorogenic acid content. Fang et al. (2022) found that steaming was the most thrifty, followed by microwaving and boiling, while frying and baking decreased it more. Lachman et al. (2013) found that boiling potatoes preserve 50 %, microwaving 28 % and baking 37 % of the chlorogenic acid content in raw potatoes.

Peeling raw potatoes decreases the chlorogenic acid content to 65,7 %, so the peel contains about 34,3 % of chlorogenic acid (Lachman et al., 2013).

Flavonoids – anthocyanins

Flavonoids are effective antioxidant and important free radical scavengers. The most abundant flavonoids in white-fleshed and yellow-fleshed potatoes are catechin and epicatechin at level of 30 µg/100 g FW, but colour-fleshed potatoes contain more than twice the amount of potatoes with white and yellow flesh, because they contain high amount of the colour pigments anthocyanins (Brown, 2005). Flavonoids are increased by stress conditions such as warm and dry weather (Escuredo et al., 2018).

Anthocyanins are chemical pigments commonly found in red to blue flowers, fruits, and vegetables and in tubers of red and purple fleshed potatoes. Anthocyanins have many beneficial functions in promotion human health such as antioxidant, anti-inflammatory and anti-cancer, anti-diabetic, they improve the cardio-vascular system and gut health, so anthocyanins are receiving more attention in human nutrition and health (Burgos et al., 2020; Hellmann et al., 2021).

Red and purple flesh potatoes contain about 40 mg/100 g FW anthocyanins. Red-fleshed potatoes contain acylated glucosides of pelargonidin, while purple ones contain acylated glucosides of malvidin, petunidin, peonidin and delphinidin (Brown, 2005). The intensity of the flesh colour has a positive effect on the anthocyanin content, so the darker the colour of flesh, the higher the anthocyanin content (whether red or purple). Hejtmánková et al. (2013) found that they contain 210 – 2419 mg/kg DM cyanidin equivalents (where cyanidin is one of the anthocyanins), also Lachman et al. (2013) found 161 – 2420 mg/kg DM cyanidin equivalents and Hamouz et al. (2018b) found 17-750 mg/kg FW cyanidin equivalents. Most anthocyanins are in the flesh, because peeling of raw potatoes increases their content (Lachman et al., 2013).

Higher altitude leads to higher anthocyanin content (compared Valečov (460 m asl.) 943 mg/kg DM to Přerov nad Labem (178 m asl.) 629 mg/kg DM) (Hejtmánková et al., 2013), the same effect was found by Hamouz et al. (2018b), because there was 1,24 times higher anthocyanin content in highlands than in lowlands in the Czech Republic. Low temperature and high light intensity induce the anthocyanin synthesis (Ieri et al., 2011).

Weather also influences the anthocyanin content, because comparison of growing years showed that dry years increased anthocyanin content in potato tubers (Hamouz et al., 2018b).

During storage (after 6 months at 4 ^{o}C) the anthocyanin content increased in five varieties by 13,3 – 77,6 % compared to the post-harvest content, probably due to the biosynthesis of these antioxidants rather than due to the reduction in dry matter. On the other hand four varieties decreased anthocyanin content by 21,3 – 30,3 % and one variety didn't significantly change the anthocyanin content (Hamouz et al., 2018b).

Cooking increases the anthocyanin content compared to raw potatoes. Boiling increased by 3,79 times, microwaving by 3,06 times and baking by 2,94 times. These changes depend on the variety and its raw content, as e.g. variety Violette with the highest content in raw tubers increased the anthocyanins the least (Lachman et al., 2013). On the other hand some research found decrease of anthocyanins while microwaving by 16-29 % (Mulinacci et al., 2008).

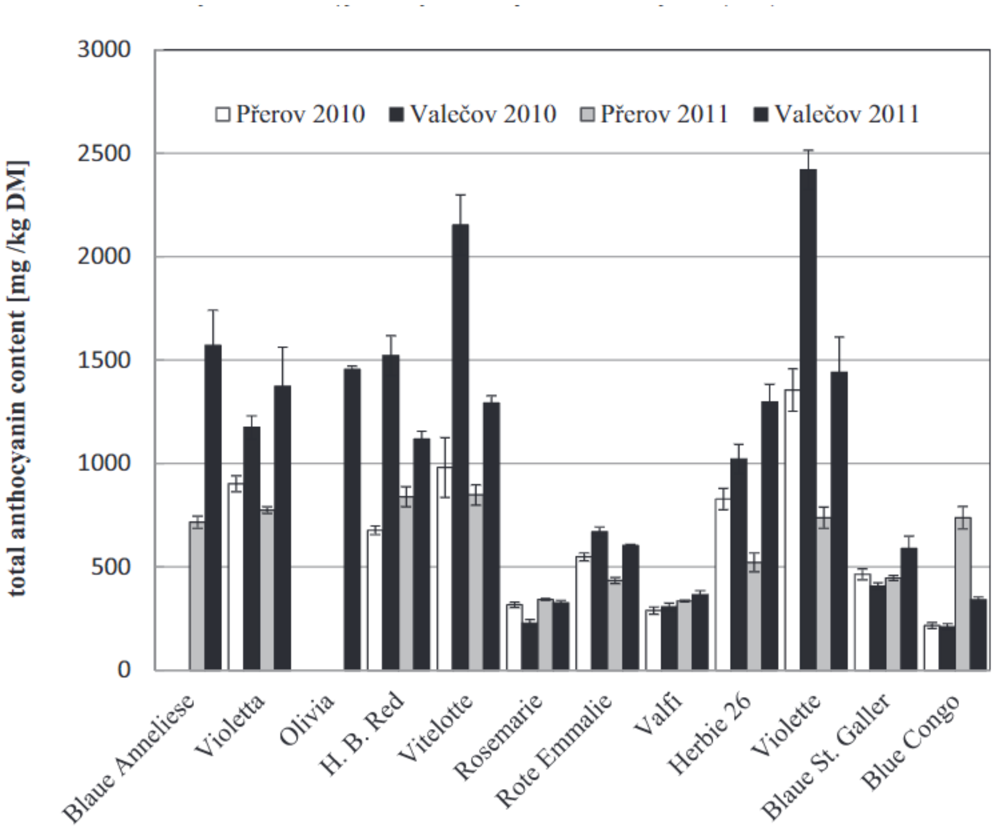

Figure 16: Anthocyanin content in colour-fleshed potatoes depending on the year and locality (Hejtmánková et al., 2013).

L-tyrosine

L-tyrosine is one of the 20 basic amino acids that make up all proteins in all organisms. It is one of the most abundant phenolic compound in plant tissues, including potatoes, where its content ranges from 770 to 3900 mg/kg (Lachman and Hamouz, 2005).

This non-essential amino acid can be synthesised to some extent by the human body. It is a precursor to produce important substances in the human body such as the hormones adrenaline, noradrenaline, and dopamine, as well as the thyroid hormones (tyrosine and triiodothyronine) and the pigment melanin.

However, tyrosine has a negative effect on the discolouration of potato flesh, as it is one of the precursors that react with polyphenol oxidase after cell breakdown to produce dark pigments (Stevens et al., 1998).

Carotenoids

Carotenoids are yellow and orange (and sometimes yellow-green and red) lipophilic pigments found in the bodies of plants, animals, fungi, and microorganisms. As they are photosynthetically active compounds, they participate to some extent in photosynthesis and protect chlorophylls from excessive radiation and dangerous reactive oxygen species and damages (Kotíková et al., 2008). They are antioxidants and, for example, beta-carotene is also a provitamin of vitamin A. They support the immune system and prevent against the development of cancer and cardiovascular diseases. Lutein and zeaxanthin were found to be important in slowing down the ageing process (Ducreux et al., 2005; Lachman et al., 2016).

The carotenoids found in potatoes belong to the group of xanthophylls (their colour spectrum ranges from yellow to reddish-purple) and these are mainly lutein, zeaxanthin, and violaxanthin. Most carotenoids are found in tubers with yellow and red flesh, but a very small amount is also found in tubers with white flesh (Brown, 2005; Lachman et al., 2016). The content of carotenoids is strongly correlated with the yellowness index of potato flesh (Tatarowska et al., 2019). Kotíková et al. (2016) report that the content of carotenoids was significantly higher in varieties with yellow flesh (26,2 mg/kg dry matter) than in varieties with red or purple flesh (5,69 mg/kg dry matter) and there were also found significant differences between the varieties (Kotíková et al., 2007). They also state that antheraxanthin was the main carotenoid in varieties with yellow flesh and neoxanthin was the main carotenoid in varieties with red flesh. Hejtmánková et al. (2013), on the other hand, report that in the varieties they studied, there was a weak positive correlation between the anthocyanin and carotenoid content, so some varieties may contain high amounts of both anthocyanins and carotenoids.

In potatoes with white flesh, the content of carotenoids is 50-100 µg/100 g FW, but in potatoes with dark yellow to orange flesh, the values reach up to 1000 µg/100 g FW (Brown et al., 2008). Tatarowska et al. (2019) report that the average value of the examined varieties ranges from 5,6 to 20 mg/kg FW., There are 0,779-13,3 mg/kg DM of carotenoids, of which 54-93 % is lutein (Hejtmánková et al., 2013).

The total content of carotenoids is statistically significantly higher when potatoes are grown at higher altitudes (Valečov) compared to lower altitudes (Přerov nad Labem) in both studied years (2010 and 2011). This can be explained by the fact that carotenoids are photosynthetically active pigments, and solar radiation which is higher at higher altitudes (which was recorded higher in Valečov in highlands than in Přerov nad Labem in lowlands) induce the formation of photosynthetically active pigments and thus carotenoids. They also report that the intensity of UV radiation, which also induces the formation of carotenoids, is correlated with altitude (Hejtmánková et al., 2013). There are also reports that the content of carotenoids is statistically significantly correlated with the average temperature during the vegetation period of the year (Escuredo et al., 2018; Hejtmánková et al., 2013; Lachman et al., 2016).

A statistically significant effect of the year on the carotenoid content was also observed in both studied locations (Valečov and Přerov nad Labem). In 2011, the carotenoid content of potatoes was higher than in 2010, which can be attributed to the warmer weather and higher solar radiation in 2011 (Hejtmánková et al., 2013). Kotíková et al. (2008) reported that the mean total carotenoid content was statistically significantly higher among the eight examined varieties in 2005 (20,9 mg/kg fresh weight) than in 2004 (5,8 mg/kg fresh weight).

The carotenoid content decreases during cooking (Lachman et al., 2016). Kotíková et al. (2016) reported that the content decreased by 92 % during boiling and by 88 % during baking, with lutein being the most stable during cooking methods (for potatoes with yellow flesh, a decrease of 19% during boiling and 40% during baking was observed), followed by beta-carotene, but other carotenoids were degraded by almost 100 %. However, in the research by Tian et al. (2016), the losses of carotenoids during potato cooking were lower, with only a 20% decrease during boiling and a 52% decrease during baking.

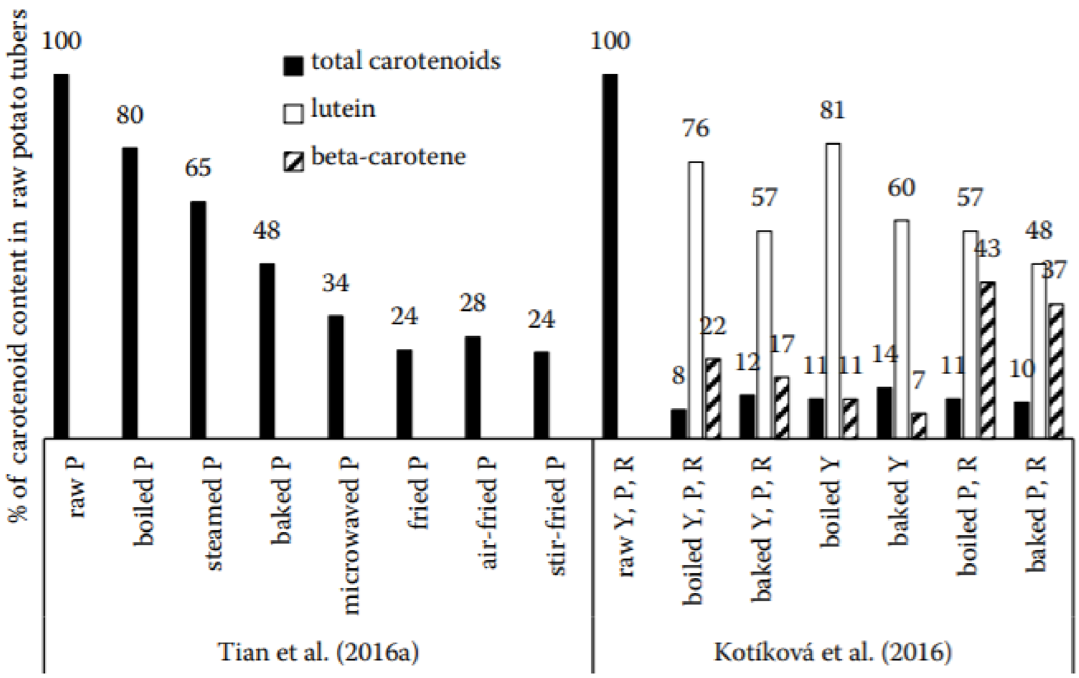

Figure 17: Percentage of carotenoids in potatoes after different cooking methods compared to raw potatoes (100%) (Lachman et al., 2016).

After storage (9 months at 4 ^{o}C), the carotenoid content decreased only slightly (however, the content of lutein, which is an important component of carotenoids, increased slightly, but zeaxanthin and antheraxanthin decreased) (Lachman et al., 2016).

α-lipoic acid

α-Lipoic acid is found in all prokaryotic and eukaryotic cells. In potatoes, as in other foods, it is present only in small amounts, but it is an important and unique antioxidant because it has these properties in both its oxidised and reduced forms. It is also known as a growth factor for potatoes and certain other organisms (bacteria and protozoa), thus promoting the growth of the whole organism and parts of it. Both α-lipoic acid and its reduced form can scavenge reactive oxygen species and also refresh other antioxidant substances (Navari-Izzo et al., 2002).

Glycoalkaloids

Glycoalkaloids (95 % is made up of solanine and chaconine) are potentially harmful substances found in potatoes that cause a bitter taste in high concentrations. They are secondary metabolites of plants that serve as protection against potential attack by pathogens and pests (Burgos et al., 2020). Potatoes with a maximum glycoalkaloid content of 200 mg/kg fresh weight are considered safe, but usually only tens of mg/kg fresh weight are present (Ruprich et al., 2009). Lachman et al. (2001) reported that potatoes contain an average of 75 mg/kg glycoalkaloids and that potatoes taste bitter if they contain more than 140 mg/kg glycoalkaloids. Glycoalkaloids (including those in potatoes) have also been found to have potential pharmaceutical uses in cancer treatment (Friedman, 2015).

Most glycoalkaloids are found in the skin of the potato, and after peeling, the total glycoalkaloid content is reduced to 34.7% (Lachman et al., 2013), but Tajner-Czopek et al. (2012) found reduction only by 20 % in coloured flesh potato varieties. Muñoa et al. (2022) found a reduction in total glycoalkaloids by 5-73 % with an average reduction by 33 % after peeling.

Variety and its genotype have a statistically significant effect on glycoalkaloid content in potato tubers. The content can also be increased by exposure to light, mechanical injury, storage and heat and draught stress during growth (Burgos et al., 2020). After exposure tuber to light for 14 days, the content of glycoalkaloids increased, with the highest accumulation on the 11th day of exposure to light. There was also observed that washed potatoes accumulated more glycoalkaloids than unwashed potatoes (Rymuza et al., 2020).

No statistically significant difference was observed during storage compared to the glycoalkaloid content immediately after harvest (Hajšlová et al., 2005).

Cooking resulted in a significant reduction of glycoalkaloid content to 26 % of the original value determined in raw potatoes, while baking and microwave treatment reduced the amount of glycoalkaloids to about half of the content in raw tubers (Lachman et al., 2013). Tajner-Czopek et al. (2012) also found a reduction, which was the lowest in cooked unpeeled (by 8 %) and cooked peeled (by 39 %) compared to raw material, the highest decrease was found in crisps (by 83 %) and French fries (by 94 %).

Nitrates

Nitrates are substances that, in high concentrations, can have potentially negative effect on human health if they are converted into nitrites in the body. When nitrite enters the blood and binds to haemoglobin, it forms methaemoglobin, which loses its ability to carry oxygen to tissues. Infants are more susceptible to nitrite damage of haemoglobin. In the general population, nitrate intake is very low and below the safe daily intake limit set by EFSA (European Food Safety Authority) on 3,7 mg per kilogram of body weight per day (3,7 mg/kg bw/day) (EFSA, 2017).

Conventionally grown potatoes contain usually the average of 150 mg/kg FW (Lachman et al., 2005; Pobereżny et al., 2015), with range 4-840 mg/kg (Mozolewski and Smoczynski, 2004).

The nitrate content of potato tubers is largely influenced by the genotype of the variety (Lachman et al., 2005; Rymuza et al., 2020). Nitrate content is also influenced by weather conditions during the growing season. In hot and dry weather, nitrate accumulation is higher than in cooler and wetter weather (Zgorska and Frydecka-Mazurczyk, 2000). Hamouz et al. (2005) reported that nitrate content in tubers was significantly higher at lower altitudes due to higher temperatures and more intense drought, which limit photosynthesis and the incorporation of nitrogenous substances into proteins. Excessive rainfall at the end of the growing season with a lack of sunlight also limits photosynthesis and increases nitrate accumulation in potato tubers (Hamouz et al., 1999).

At full maturity (harvested in September), the nitrate content was lower than in immature tubers harvested in August (Zgorska and Frydecka-Mazurczyk, 2000).

The nitrate content depends on nitrogen fertilization. The nitrate content of potato tubers is higher on more fertile soils (Hamouz et al., 2005; Zgorska and Frydecka-Mazurczyk, 2000) and under conventional farming regime compared to organic farming regime. (Hajšlová et al., 2005; Lombardo et al., 2017).

Raw potatoes contain in average 62-125 mg/kg FW depending significantly on the variety (Rymuza et al., 2020). Peel contain 35 % more nitrates than the flesh and boiling decreases the nitrate content by 59,7 %, while frying increased it by 52 % (Ebrahimi et al., 2020).

The nitrate content increased during 14 days light exposure linearly by 1-2 mg/kg FW depending on the variety, with no differences between washed and unwashed tubers (Rymuza et al., 2020).

Acrylamide

Acrylamide is a potentially carcinogenic substance that is formed at high temperatures during frying or baking by the Maillard reaction, in which reducing sugars react with amino acids (mostly asparagine). The Maillard reaction occurs in many foods that are baked or fried, including potatoes. In this reaction, the reducing sugar content is usually the limiting substance, and therefore the reducing sugars in chips or French fries' potatoes are controlled. Acrylamide level is higher when the products are fried to a dark colour and at high temperatures, so frying at a lower temperature and for a longer time is more recommended (Vreugdenhil et al., 2011).

In 2002 acrylamide was discovered in common foods including potato chips and crisps, coffee, biscuits, breads etc. prepared at high temperatures (>120 ^{o}C) with low moisture. Acrylamide was classified as probable human carcinogen (group 2A) by the IAFC (International Agency for Research on Cancer) in 1994 (Hyslop, 2022). To reduce acrylamide content, the European Union has published Acrylamide benchmarks levels (COMMISSION REGULATION (EU) 2017/2158). The acrylamide content should be below these levels, but if it is above, the products should be improved according to the recommendations to reduce the acrylamide content, but it can still be sold.

BENCHMARK LEVELS REFERRED TO IN ARTICLE 1(1)

Benchmark levels for the presence of acrylamide in foodstuffs referred to in Article 1(1) are as follows:

Food	Benchmark level [μg/kg]
French fries (ready-to-eat)	500
Potato crisps from fresh potatoes and from potato dough Potato-based crackers Other potato products from potato dough	750
Soft bread (a) Wheat based bread (b) Soft bread other than wheat based bread	 50 100
Breakfast cereals (excl. porridge) — bran products and whole grain cereals, gun puffed grain — wheat and rye based products (1) — maize, oat, spelt, barley and rice based products (1)	 300 300 150
Biscuits and wafers Crackers with the exception of potato based crackers Crispbread Ginger bread Products similar to the other products in this category	350 400 350 800 300
Roast coffee	400
Instant (soluble) coffee	850
Coffee substitutes (a) coffee substitutes exclusively from cereals (b) coffee substitutes from a mixture of cereals and chicory (c) coffee substitutes exclusively from chicory	 500 (2) 4 000
Baby foods, processed cereal based foods for infants and young children excluding biscuits and rusks (3)	40
Biscuits and rusks for infants and young children (3)	150

(1) Non-whole grain and/or non-bran based cereals. The cereal present in the largest quantity determines the category.
(2) The benchmark level to be applied to coffee substitutes from a mixture of cereals and chicory takes into account the relative proportion of these ingredients in the final product.
(3) As defined in Regulation (EU) No 609/2013.

Figure 18: Benchmark levels of acrylamide (Commission regulation (EU) 2017/2158).

The acrylamide content therefore depends mainly on the content of reducing sugars in raw tubers. The content of reducing sugars in potatoes is mainly influenced by variety (Elmore et al., 2015) and storage temperature, which should be around 8-9 °C for chips and 7-9 °C for fries using sprouting inhibitors (Bárta et al., 2008; Vokál, 2013). A variety resistant to increasing the content of reducing sugars when stored at lower temperatures would be most effective in reducing acrylamide content in potato products (Rosen et al., 2018).

At higher altitude, lower temperature and more humid climate, potatoes have higher levels of reducing sugars and thus higher levels of acrylamide in potato products from these areas (Vokál, 2013). This is also related to the fact that in warmer areas of lower altitude, potatoes ripen faster, and mature potatoes contain lower levels of reducing sugars, which are precursors of acrylamide. However, it is not advisable to harvest potatoes for frying too late, because of the risk of temperatures falling below 8 °C, which can increase reducing sugar content. Heat and drought stress is another risk factor which higher acrylamide levels (Rosen et al., 2018).

The level of nitrogen fertilization also influences the acrylamide content, because the higher the nitrogen dose, the higher the asparagine content in potatoes and the higher the acrylamide content in fried potato products. But this is usually not a problem, because reducing sugars are limiting in Maillard reaction (Vokál 2013; Čepl et al. 2014).

PART 2: HEALTH BENEFITS AND RISKS OF POTATO CONSUMPTION

Introduction

According to FAO (2021) potatoes are worldwide the fourth most important food crop (following rice, wheat, and maize) with 376 million tonnes harvested from 18,1 million hectares with average yield 20,7 t/ha. Potatoes have so far been seen as both good and bad. On the bad side, they have been attributed with causing obesity (because of high starch content) and type 2 diabetes and associated diseases (Burlingame et al., 2009). However, potatoes have many positive qualities such as low energy density, no fat, gluten-free, high satiating effect, high potassium content and a wide range of antioxidants including high amount of vitamin C (Beals, 2019; Burgos et al., 2020; Burlingame et al., 2009).

Antioxidants and anti-inflammatory effect

Most of the health benefits of potatoes are due to their high content and wide range of antioxidants, which can scavenge free radicals - so-called reactive oxygen species (ROS). The main antioxidants are phenolics, vitamin C, E and B6, carotenoids, selenium, and lipoic acid. Red and purple flesh potatoes have high antioxidant activity due to their high anthocyanin content. The total phenolic intake of potatoes is the third highest compared to other vegetables and fruits (following oranges and apples) and it also stands out above, for example, strawberries and blueberries because their relatively low consumption (Chun et al., 2005).

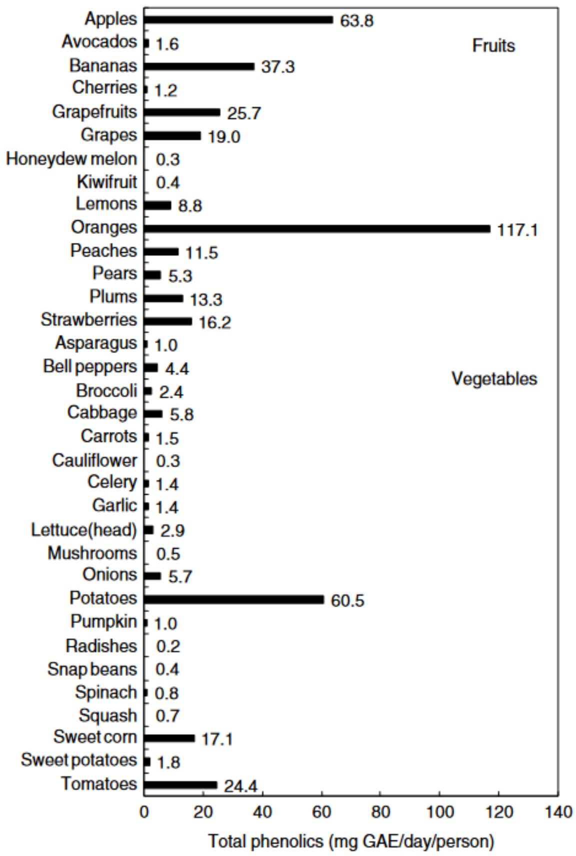

Figure 19: Comparison of total phenolic intake from daily fruit and vegetables consumption (Chun et al., 2005).

Chlorogenic acid in white, yellow and coloured (red and purple) fleshed potatoes is a strong antioxidant, that can reduce lipidic oxidation and thus protect cell walls from damage by reactive oxygen species (Visvanathan et al., 2016).

It is also important to note that almost 50% of phenolic compounds is contained in the skin and near the skin (Visvanathan et al., 2016), so the effect is higher when eating potatoes with skin.

Comparing the effects of eating potatoes with white, yellow and purple flesh, it was found that eating yellow and purple potatoes reduced DNA damage by reactive oxygen species and purple potatoes also reduced CRP (an indicator of inflammatory processes in the body) compared to eating potatoes with white flesh (Kaspar et al., 2011).

Patatin, the most abundant protein in potatoes, can also scavenge reactive oxygen species so it has the antioxidant ability (Hellmann et al., 2021).

Cancer prevention

Phenolic compounds (mainly chlorogenic acid and anthocyanins), dietary fibre, glycoalkaloids, protease inhibitors and carotenoids are considered to be potent anticancer compounds in potatoes. The most important anticancer substance is chlorogenic acid, which has been shown to inhibit the development of colon and liver cancer (Wang et al., 2011). Potatoes with coloured flesh (red and purple) contain anthocyanins, which inhibit cancer cell proliferation and promote cell apoptosis (programmed cell death, which physiologically prevents uncontrolled cancer growth in the body) (de

Arruda Nascimento et al., 2022). Diet rich in antioxidant carotenoids and flavonoids (including anthocyanins) are associated with a lower incidence of certain cancers (Brown, 2008).

Although glycoalkaloids (especially solanine) have long been considered only as toxins, they have been found to inhibit cancer cell growth and induce apoptosis (Nkwe et al., 2021). They may therefore be part of future cancer drugs, but further research is needed. It was also reported that chaconin has even higher biological activity in this field than solanine (Friedman et al., 2005).

A diet rich in vegetables and fruits, with potato being the commonly consumed vegetable, high in fibre, resistant starch and phenolics can decrease colon cancer risk by 40 % (Vanamala, 2019).

Effect on cardiovascular diseases

Potassium, antioxidants (including phenolic compounds, vitamin C) and fibre have a positive effect on the cardiovascular system (Hellmann et al., 2021). Potato consumption has been shown to reduce blood pressure, improve lipid profiles and reduce markers of inflammation, thereby improving cardiometabolic health (McGill et al., 2013). As inflammation has a negative effect on the cardiovascular system, all the antioxidants with free radical scavenging activity also have an indirect positive effect on the cardiovascular system (Camire et al., 2009).

Low glycaemic index (GI) diet is associated with a reduced risk of cardiovascular diseases, type-2 diabetes, and obesity. Boiled potatoes have quite high GI (89,4), but if the boiled potato is chilled for 12-24 hours the GI is reduced to only 56,2 due to the formation of resistant starch (Camire et al., 2009).

Ideally prepared potato for cardiovascular health are low in fat and sodium, and even better when boiled and cooled and eaten with the skin on (because there is the most of potassium and fibre) (Camire et al., 2009).

Reduction of high blood pressure

A high intake of potassium is effective in lowering blood pressure, and potatoes are high in potassium and low in sodium (high sodium intake increases the blood pressure). Most of the potassium in potato tuber is in the skin, so it is best to eat potatoes with the skin on. Potatoes contain more potassium than other fruits and vegetables. Many studies have reported that increasing the ratio of potassium to sodium in the diet leads to a reduction in blood pressure and a lower risk of stroke (Appel et al., 2006; Camire et al., 2009). The proteins in potatoes also reduce vasoconstriction and the secretion of hormones that raise blood pressure (Visvanathan et al., 2016).

Vitamin B6 has also been found to have a potential to reduce high blood pressure, as experiments in obese rats found that a high dose of vitamin B6 in the diet lowered their blood pressure, and when vitamin B6 was removed from the diet, blood pressure increased again(Lal et al., 1996). Other vitamins and antioxidants in potatoes - vitamin C and E, carotenoids, phenolics and lipoic acid - also have a beneficial effect on reducing high blood pressure (Vasdev et al., 2002).

Vinson et al. (2012) reported that when people with high blood pressure consumed 6-8 small purple-fleshed microwaved potatoes twice a day for 4 weeks there was a 4,3% significant reduction in diastolic blood pressure and a 3,5% reduction in systolic blood pressure compared to no potato variant. This was due to the high anthocyanin content and high potassium content of the potatoes eaten with the skin. Purple potatoes are an effective in lowering blood pressure, risk of heart disease and stroke in hypertensive people without weight gain. However, this study was conducted on a small sample and more research is needed to confirm this claim. Schwingshackl et al. (2019) reported that high French fries consumption was associated with an increased risk of hypertension, whereas boiled, baked and mashed potatoes were not associated with an increased risk of hypertension.

On the other hand, it has been reported that potatoes have a high glycaemic index and high starch content and thus potatoes may increase blood pressure. The glycaemic index of a food can be reduced by combining it with another food that has a low glycaemic index, thereby reducing the release of sugar into the bloodstream. Borgi et al. (2016) reported that eating more than 4 servings of boiled, baked, or fried potatoes was associated with an increase in blood pressure in the participants in their study, compared with eating only one serving of potatoes per month. However, this increased risk is probably due to the fact that potatoes are usually eaten with high amounts of salt, which is a source of sodium, or high amounts of fat (saturated fatty acids and trans-fatty acids), which are risky for increasing blood pressure. Aljuraiban et al. (2020) also found that boiled, mashed or baked potatoes didn't increase the blood pressure, while fried potatoes did and also increased the BMI in the US women. On the other hand, no significant increase was found in US men.

Hu et al. (2017) studied the effect of potato consumption on blood pressure change (on adults in Spain) and found that eating potatoes did not either increase blood pressure or the risk of hypertension.

The effect of potatoes on blood pressure is not entirely clear, precisely because they are high in potassium, which lowers blood pressure, but also contain high levels of starch, which can increase blood pressure (Borgi et al., 2016).

Lowering cholesterol

Cholesterol reduction has been associated with the protein, resistant starch and phosphorylated starch (phosphorylated starch is associated with lower levels of fatty acids in the blood and a positive effect on blood lipid lowering, even higher than resistant starch), fibre, glycoalkaloids (they have a high affinity for cholesterol) and phenolic compounds found in potatoes (Burgos et al., 2020; Camire et al., 2009).

Eating potatoes with the skin on has a positive effect on lipid metabolism and thus has a positive effect on lowering plasma and liver cholesterol, which in turn reduces the risk of cardiovascular disease (Robert et al., 2006).

Resistant starch promotes the production of bile acids, and this also leads to a reduced concentration of cholesterol in the blood serum and reduces the synthesis of fatty acids (lipids) in the body (Hashimoto et al., 2006).

The peptides and proteins in potatoes also have a positive effect on increasing 'good' HDL cholesterol and reducing all other so-called 'bad' non-HDL cholesterol (Burgos et al., 2020).

Effect on human weight and satiety

Potatoes themselves contain almost no fat, are high in water and low in energy. An increased risk of weight gain and obesity is associated with fried potato products, which are high in fat, energy and usually also salt. According to Randolph et al. (2014) and Vinson et al. (2012), there is no significant association between weight gain and potato consumption compared to no potato consumption. However, many observational studies report that potatoes increase weight, but this cannot be considered causal as the results are influenced by many factors.

People feel more satiated after eating boiled potatoes compared to eating chips (French fries) and pasta of the same energy value (Geliebter et al., 2013; Leeman et al., 2008). Boiled potatoes have the highest satiating effect compared to conventional foods (Figure 20) (Holt et al., 1995), so it is more satiating than other side dishes such as rice and pasta (Robertson et al., 2018). Potatoes could therefore help to maintain weight and prevent obesity.

Bakery Products
Croissant 47%
Cake 65%
Doughnuts 68%
Cookies 120%
Crackers 127%

Snacks and Confectionary
Mars candy bar 70%
Peanuts 84%
Yogurt 88%
Crisps 91%
Ice cream 96%
Jellybeans 118%
Popcorn 154%
All-Bran 151%
Porridge/Oatmeal 209%

Breakfast Cereals with Milk
Muesli 100%
Sustain 112%
Special K 116%
Cornflakes 118%
Honeysmacks 132%

Carbohydrate-Rich Foods
White bread 100%
French fries 116%
White pasta 119%
Brown Rice 132%
White rice 138%
Grain bread 154%
Whole meal bread 157%
Brown pasta 188%
Potatoes, boiled 323%

Protein-Rich Foods
Lentils 133%
Cheese 146%
Eggs 150%
Baked beans 168%
Beef 176%
Ling fish 225%

Fruits
Bananas 118%
Grapes 162%
Apples 197%
Oranges 202%

The list with the most filling food at the top

Potatoes, boiled 323%
Ling fish 225%
Porridge/Oatmeal 209%
Oranges 202%
Apples 197%
Brown pasta 188%
Beef 176%
Baked beans 168%
Grapes 162%
Whole meal bread 157%
Grain bread 154%
Popcorn 154%
Eggs 150%
Cheese 146%
White rice 138%
Lentils 133%
Brown Rice 132%
Honeysmacks 132%
All-Bran 151%
Crackers 127%
Cookies 120%
White pasta 119%
Bananas 118%
Jellybeans 118%
Cornflakes 118%
Special K 116%
French fries 116%
Sustain 112%
White bread 100%
Muesli 100%
Ice cream 96%
Crisps 91%
Yogurt 88%
Peanuts 84%
Mars candy bar 70%
Doughnuts 68%
Cake 65%
Croissant 47%

Table adapted from S.H.A. Holt, J.C. Brand Miller, P. Petocz, and E. Farmakalidis, "A Satiety Index of Common Foods," European Journal of Clinical Nutrition, September 1995, pages 675-690.

Figure 20: Index of satiety after consumption of the food. White bread is taken as reference (100 %). Boiled potatoes have the highest satiety index compared to all other foods (Holt et al., 1995).

Eating crisps or chips does lead to weight gain, but we have to consider that this is mainly influenced by the fat consumed with potatoes. Borch et al. (2016) report that in 3 out of 3 studies, confirm that eating chips (French fries) increases body fat, but the other treatments of potatoes (excluding French fries) didn't have such clear results (2 studies reported a neutral effect and 2 studies a positive effect of potato consumption on obesity). Andersen et al. (2018) compared different studies on the effect of potatoes and potato products on human weight and found no studies showing that eating potatoes increases weight, but eating fried potato products increases weight. In general, the thinner the French fries or chips, the more fat they contain, because they have a larger surface area through which the fat is absorbed.

The protease inhibitor that is contained in potatoes promotes the release of cholecystokinin, which makes you feel full, and people lose weight when they eat this substance. Proteins in potatoes can also indirectly inhibit absorption by inhibiting the proteolytic enzyme trypsin (Visvanathan et al., 2016).

The phenolics which are present in high concentrations (up to 50 %) in the skin but also in flesh, increase satiety and thus reduce food intake (Hellmann et al., 2021).

In addition, carotenoids and anthocyanins from coloured sweet potatoes were found to reduce the rate of body fat deposition in experiments on mice (Kim et al., 2020). Yildiz et al. (2021) reported that anthocyanins limit lipid metabolism, reduce lipid uptake, decrease energy intake and, in turn, increase energy expenditure of the body.

Antidiabetic effect and glycaemic index

Potatoes are considered by the general public to be a food with a relatively high glycaemic index. In fact many studies have shown that fried or boiled potatoes increase the risk of type 2 diabetes (Muraki et al., 2015), but when potatoes were substituted for whole grains, this risk would increase even more (Halton et al., 2006). However, Johnston et al. (2020) found that when potatoes were compared with white bread as a side dish, there was no increase in blood glucose and, on the contrary, the potato variant had a higher nutritional value, higher potassium content and higher fibre intake. Potato consumption was not found to increase the risk of cardiovascular disease.

Muraki et al. (2015) reported that eating boiled potatoes, baked potatoes, mashed potatoes, and French fries more than once a week increased the risk of type 2 diabetes, with French fries contributing the most to this increased risk. Borch et al. (2016) reported that 3 of 3 studies found that eating French fries increased the risk of type 2 diabetes, but the results were not as clear for other potato treatments (5 studies reported a neutral or negative effect and 2 studies reported a positive effect). Schwingshackl et al. (2019) also found that French fries increased the risk of type 2 diabetes, but boiled potatoes only slightly increased this risk. Carotenoids and phenolics have a positive effect on reducing the risk of type 2 diabetes (Hellmann et al., 2021)

However, the potato skin contains large amount of phenolic substances (up to 50% of the total amount in potatoes), which have the ability to reduce hyperglycaemia (Singh et al., 2005). Another abundant substance in potatoes is chlorogenic acid, which reduces the rate of sugar release into the bloodstream and is considered to prevent the development of type 2 diabetes and thus reduces the glycaemic index of foods (Visvanathan et al., 2016).

Heat treatments has a major effect on the glycaemic index, while variety, maturity, starch texture and storage have a minor effect. Cooling potatoes after cooking (and reheating) causes retrogradation of starch - the conversion of some of the fast-digestible starch (mainly amylose), which increases the glycaemic index the most, into slow-digestible and resistant starch, which passes through to the large intestine, where it acts similarly to fibre. This can reduce the glycaemic index from 89 to 56 (Camire et al., 2009).

French fries have a lower glycaemic index, a higher proportion of resistant starch, but also a lower satiating capacity than boiled potatoes. The glycaemic index changes when different foods are eaten together. For example combining potatoes with fat significantly reduces the GI by 58%, whereas combining potatoes with protein reduces the GI by 18% (Leeman et al., 2008; Nayak et al., 2014).

However, the glycaemic index depends not only on the heat treatment and temperature at which the potato is consumed, but also on the variety (Fernandes et al., 2005). It has been found that floury varieties (high in dry matter and high in starch) have a higher GI, while firm (salad) and soft-very early varieties (high in moisture and low in starch) are classified as having a medium GI (Nayak et al., 2014).

Andersen et al. (2018) studied effect of boiled potato varieties with different glycaemic index (Carisma with GI 53, Arizona with GI 93) and found no difference in feeling hunger 2 hours after consumption. However, it is generally reported that foods with a low glycaemic index prolong the duration of feeling full, but it is very difficult to conduct long-term studies on this topic and the glycaemic index is highly influenced by the food eaten together with potatoes.

Small and immature potatoes have a lower GI than large and mature potatoes (Nayak et al., 2014).

Effect on gut health

Potatoes contain fibre and resistant starch, which have a positive effect on colon microbiota and colon health. The starch contained in raw potatoes is resistant to digestion and acts in a similar way to fibre. Some of the starch in potatoes remains in a resistant form even after cooking treatments. When potatoes are cooled after cooking, starch retrogradation occurs, whereby the molecules, mainly amylose, form molecules of resistant starch that are more resistant to digestion. This process is influenced by many factors such as salt, sugar or lipid content (Nayak et al., 2014). For example French fries contain more resistant starch than cooked potatoes, where starch retrogradation is more intense (Nayak et al., 2014).

Diet influences the composition of the microbiota in the colon. The composition of the microbiota affects the absorption of various substances and has an impact on weight gain and gut health. Several studies have shown that anthocyanins have been found to have a positive effect on modifying the colonic microbiota (increasing the amount of *Lactobacilli* or *Bifidobacteria*). Thus, anthocyanins are probiotics that serve to support the so-called "good" bacteria in the intestinal tract and promote bacteria that reduce excessive fat deposition (Yildiz et al. 2021). The phenolic compounds found in potatoes also have a positive effect on gut health (Hellmann et al., 2021).

Conclusion

Potatoes are an exceptional source of low-calorie energy and a wide range of health-promoting nutrients. High in vitamin C, antioxidants and other key vitamins and nutrients, they are an excellent ingredient for any health-conscious diet. Cooling after boiling, steaming without peeling, and other preparation methods may further boost potatoes' health benefits.

Although tremendous strides have been made educating the general public in recent years, many continue to view the potato as little more than a common side dish. Public communication should continue to dispel common misconceptions and promote the scientific consensus on the health benefits of potatoes.

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