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Physicochemical and Sensory Properties of Potato Snacks Fortified with *Spirulina (Arthrospira platensis)*

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ABSTRACT

The food industry has been working to decrease artificial additives while simultaneously creating products that contain ingredients that have positive effects on human health and enhance physical and mental well-being, as well as essential nutrients. Recently, spirulina has gained increased recognition as a functional food due to its antioxidant, immune system-modulating, and cholesterol-lowering qualities. In this regard, the focus of this research was to study the nutritional characteristics of dried spirulina algae and assess the impact of spirulina powder as a novel ingredient in the construction of potato snacks by analyzing the physicochemical and sensory aspects of the snack samples containing 1.5, 2.5, 3.5 and 5% spirulina powder. According to the obtained results, spirulina recorded the highest value of protein, fat, crude fiber, ash, minerals and antioxidants, which reflected on the spirulina enriched potato snacks physicochemical and sensory aspects in comparison to the control sample. Spirulina enriched snack provides a substantial amount of protein and antioxidants including phycocyanin, chlorophyll a and carotenoids. Enrichment of snacks resulted in an improvement in texture attribute, while other attributes decreased by increasing the spirulina fortification concentration; however no significant ($p \leq 0.05$) differences were recorded among potato snack samples fortified with 1.5, 2.5 and 3.5% spirulina powder for taste, color, odor and texture, Meanwhile a significant difference was observed for overall palatability between samples 1.5 and 3.5%, which were acceptable.

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Introduction

Nowadays, a growing number of customers believe that eating properly and leading a healthy lifestyle may reduce their risk of chronic diseases. As an outcome of this awareness, the food sector has been working to decrease artificial additives while simultaneously creating products that contain ingredients that have positive effects on our health and enhance our physical and mental well-being, as well as essential nutrients (Bigliardi & Galati, 2013; Carpentieri et al., 2022). Functional foods are those that were confirmed to offer health benefits beyond simple nourishment and minimize disease susceptibility. Traditional foods, customized foods (fortified, supplemented, or improved), medical food products, and food products intended for specific dietary purposes are considered as functional foods (Rojo-Poveda et al., 2019).

One of the food industry's fastest-growing market segments is plant-based goods. Dietary fibers, high protein content, bioactive compounds, sterols, and polyunsaturated fatty acids are all present in fruits and vegetables, and they provide a beneficial impact on numerous bodily functions (Martin & Li, 2017). According to Ma et al. (2022), potatoes (*Solanum tuberosum*) rank as fourth in importance as a staple crop across the world, following rice, wheat, and maize. They provide a significant source of dietary fibers, vitamins, minerals, carotenoids, phenolic compounds, protein, and carbohydrates (Li et al., 2022). Potato consumption is rising considerably in low-income and food-deficit regions of the world because of the excellent nutritional quality of potatoes and the increasing cost of other staple foods like rice, wheat, and maize (Zaheer & Akhtar, 2016; Zhang et al., 2017). Potatoes are a key crop in attaining food security since they are easy to cultivate, have a high production scale, are reasonably priced, and are easily available on the market. Global potato consumption trends indicate that, although consumption in Europe is gradually decreasing, it is growing rapidly in Africa and Asia (Singh et al., 2020).

Consuming potatoes has been linked to obesity as well as diabetes mellitus, mostly due to its abundant carbohydrate content, high glycemic index (GI), and preparation as fried product (Halton et al., 2006). Nevertheless, potatoes GI differ considerably because of cultivar-specific variation in composition (Henry et al., 2005) and meal processing techniques (Fernandes et al., 2005), indicating that individual decisions can affect this adverse effect. Remarkably, amylose retrogrades to resistant starch when cooling after cooking. This slows the release of postprandial glucose and lowers GI. (Leeman et al., 2005). Recent researches on potato chemical composition has shown that potatoes contain more than just carbohydrate. In fact, it has valuable phytochemicals that could improve human health and prevent heart disease, type 2diabetes, and several types of cancer from developing. According to McGill et al. (2013), potatoes and potato-derived products have been proven to have positive effects on a number of cardio metabolic health indicators in both humans and animals, such as lowering blood pressure, improving lipid profiles, and reducing inflammation markers. Dietary fiber and phenolic compounds are particularly promising as diabetic therapeutic aids (Ong et al., 2013).

The largest markets for potato products are thriving in Asia, the Middle East, and Latin America, despite the fact that the Netherlands, Belgium, the United States, and Canada are the major merchandisers. The primary processed commodities are French fries, potato chips and other frozen products, followed by dried goods, chilled peeled potatoes, and canned products (OECD, 2021). Potato chips are the most favored snack among all age groups (Kalita & Jayanty, 2017). The international potato chips trade scale achieved USD 34.3 Billion during 2023. IMARC Group anticipated it to reach USD 43.6 Billion by the year 2032, with a growth rate of 2.6% during 2024-2032 (IMARC, 2024).

Potato chips are mainly divided into two categories: "natural potato chips," made using fresh potatoes that have been cleaned, peeled, chopped, and oil fried, and "restructured potato chips," which are prepared using potato mash or flour then shaped into a thin layer (Korea Food Industry Association and Chung-ang University Industry-academic Cooperation Foundation, 2011). Chips cooked using oil, chips coated with oil and chips free of oil are the three subcategories that fall under each of these main categories. Because of its exceptional, appealing texture and fatty flavor combination, oil-fried chips have long dominated the potato snack market among these three subcategories (Shedeed et al., 2020). This method may result in final potato chips that contain between 35-40% oil, making them a high-fat, unhealthy snack (Barreto et al., 2019). Nonetheless, the selection of low-fat and low-calorie products has increased due to rising customer demand for foods with healthier impact. The production of oil-free potato chips, a healthier substitute for conventional potato chips, is being progressively expanding in the potato snack food segment to compete in this market (Oladejo et al., 2018). Baking is regarded as a feasible alternative for frying given that it offers satisfying sensory qualities with a crisp texture and less fat content (Han et al., 2010).

Considering the popularity of snacks and their ability to improve diet’s nutritional quality, it is advised to enrich them in order to both mitigate the negative effects of snacking and positively influencing the society’s nutritional pattern (Tork et al., 2022). New edible and alternative food and protein sources are being developed by researchers as a result of the growing global population and changing consumer patterns. Animal-based sources are the primary source of protein; however, the rise in obesity, diseases, and frequent use of antibiotic in farm animals has recently raised interest in alternative protein sources (De Jesus et al., 2018).

Microalgae are a relatively new and sustainable food source of nutritious components. Proteins of superior bioavailability, carotenoids, vitamins, long-chain polyunsaturated fatty acids, phenolic compounds, and minerals are some of the many substances that these organisms are capable of producing in great quantities (Batista et al., 2017). Unlike other food sources, microalgae do not compete for arable land, and depending on their intended use, they can even be cultivated in salty water, effluent, or non-potable water. Their high biomass yield per unit area is another benefit they offer (Torres-Tiji et al., 2020). *Spirulina platensis* and *Spirulina maxima* are the two most significant species of *Arthrospira sp*., one of the most significant genera of blue green algae (De Marco et al., 2019). Mexicans dating back to the Aztec era and locals residing in central region of Africa near Lake Chad have used them as food sources (Abdulqader et al., 2000). It is widely available and sold on the market as tablets, capsules, and dry powder (Thevarajah et al., 2022). Additionally, spirulina is among the most broadly grown microalgae in worldwide (Silva et al., 2020). Meticulous Research (2023) stated that in terms of revenue, the international spirulina market is predicted to reach USD1.10 billion by 2030 with a market volume of 102,381.3 tons.

Spirulina may contain up to 70% protein, which is regarded as a high-biological-value protein since it offers all of the essential amino acids in the amounts recommended by the Food and Agriculture Organization (FAO). Therefore, it is of higher nutritional value compared with other plant-based protein sources and just as beneficial as eggs, milk, and meat (Lupatini et al., 2017). The amount of polyunsaturated fatty acids, vitamins A, D, E, K, and group B content is noteworthy to mention. Spirulina is especially beneficial for vegans and vegetarians owing to its high vitamin B12 level, as they may be at risk of vitamin B12 deficiencies due to dietary restrictions for meat products (Grosshagauer et al., 2020). Minerals as Ca, Fe, Se, F, or I could be found in considerable concentrations in spirulina (Rzymski et al., 2019). Moreover, it has significant levels of chlorophyll, polyphenols, and carotenoids (Lafarga et al., 2020). As a nutraceutical food, spirulina has been shown to be effective for several diseases. Spirulina as a dietary supplement has been shown to prevent and regulate high cholesterol, immune diseases, certain inflammatory disorders, cancer, cardiac conditions and diabetes (Sabat et al., 2025). Furthermore, considering its rich macro and micronutrients the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) have recommended spirulina as the most nutritious and most sustainable space food (in extended space missions) (Ciani et al., 2021). Recently, spirulina has regained increased recognition as a functional food due to its antioxidant, immune system-modulating, and cholesterol-lowering qualities. Furthermore, spirulina boosts the human microbiota's abundance, indicating that it could be utilized as a prebiotic (Finamore et al., 2017). Along with enhancing metabolic parameters like insulin sensitivity, inflammation reduction, total and LDL cholesterol reduction, and HDL cholesterol elevation, it also helps obese patients to lose weight (DiNicolantonio et al., 2020). Early clinical research has indicated that spirulina may have neuroprotective effects through improving brain development and enhancing language and motor skills, especially in malnourished children. Additionally, it may help relieve physical and mental exhaustion (Sorrenti et al., 2021).

Spirulina could be found in an assortment of food items, such as salad dressings, breakfast cereals, soups, instant meals, candies, baked goods, muffins, doughnuts, and juice smoothies (Lupatini et al., 2017). Spirulina has also been incorporated into dairy goods, like cheese and ice cream (Agustini et al., 2016), rice and oat snack bar (Lucas et al., 2020), pasta (Hussein et al., 2021), ricotta cheese (Ismail et al., 2023) and gelatin dessert, frozen yogurt, biscuits, potato balls, and sushi (El Shafai and Abdallah, 2023).

In this context, the objective of this study was to assess the impact of spirulina powder as an innovative component in the production of potato snacks through evaluating the physicochemical and sensory characteristics of the snack samples, using four different levels of spirulina powder.

Materials and methods

Materials

Organic potato (*Solanum tuberosum* L.) Spunta variety was provided by a private organic farm in Ibshaway, Fayoum governorate, Egypt. Sodium chloride was purchased from a local market Giza, Egypt. The blue green algae *Arthrospira platensis* provided as a dry powder were purchased from Algal Biotechnology Unit, National Research Centre, Dokki, Giza, Egypt.

All chemicals used were of analytical grade and obtained from El-Nasr Pharmaceutical Chemicals Co., Egypt. Solvents, DPPH (2, 2-diphenyl-1-picrylhydrazyl), gallic acid, and Folin-Ciocalteu reagent were purchased from Sigma-Aldrich Company (St. Louis, Missouri, USA).

Methods

Preparation of potato snacks samples

Potatoes were initially cleaned under tap water to remove dirt and other pollutants. After that, potatoes were blanched with the peel for 15 min till softening then immersed in cool water, peeled and cut into cubes, after that the potato cubes were ground for 3 min in a multifunction food processor (National, MK5070N, Japan) to obtain a uniform smooth paste. The obtained paste was mixed with 1.5% sodium chloride and 20% distilled water to obtain a homogeneous mixture. Five blends were formulated, potato mixture with no Spirulina powder addition which served as control treatment (PC), potato mixture with the addition of 1.5% of spirulina powder (PS1), potato mixture with the addition of 2.5% of spirulina powder (PS2), potato mixture with the addition of 3.5% of Spirulina powder (PS3) and potato mixture with the addition of 5% of Spirulina powder (PS4). After mixing, the mixture was made into (6cm x6cmx3 mm) discs, baked in the oven at 180°C for 12 minutes (reaching 2% moisture content), and then cooled, packaged and labeled.

Chemical analysis

Blanched potato, spirulina and potato snack samples underwent to the following chemical analyses: moisture, protein, fat, crude fiber, ascorbic acid and ash contents according to the methods (AOAC, 2012), while total carbohydrate contents were calculated by difference.

Determination of mineral content

The mineral content was determined using an atomic absorption spectrophotometer (Perkin Elmer, Model 5000, Germany) according to (AOAC, 2012) method.

Determination of total phenolic compounds (TPC)

Total phenolic compounds (TPC) were determined according to Singleton et al. (1999); the Folin-Cicalteau method was used. The absorbance of the samples was read at 760 nm, R^2=0.991. A standard curve was established expressing the results as mg gallic acid equivalents (GAE)/100g sample.

Determination of antioxidant activity

Free radical scavenging activity was done according to the technique described by (Hung & Morita, 2008) using 1,1-diphenyl-2-picrylhydrazyl (DPPH). A Jenway 6705 spectrophotometer (Dunmow, Essex, UK) was used. The absorbance of the samples was read at 515nm, R^2=0.983.

Determination of chlorophyll-a and total carotenoids

The total carotenoids and chlorophyll-a were determined according to Askar and Treptow (1993) method as follows:

Ten grams of sample were mixed with 30 ml of 85% acetone in a dark bottle and left to stand for 15 h at room temperature. The mixture was then filtered through glass wool into a 100 ml volumetric flask, and made up to the final volume with 85% acetone solution. The absorbance of the acetone extract was measured at 440, 644 and 662 nm against 85% acetone as a blank using a Jenway 6705 spectrophotometer (Dunmow, Essex, UK). The amount of the total carotenoids and chlorophyll-a were calculated according to the following equations:

$$\text{Chlorophyll (a)}=(9.784 \times Abs_{662})-(0.99 \times Abs_{644}) \quad (1)$$
$$\text{Chlorophyll (b)}=(21.426 \times Abs_{644})-(4.65 \times Abs_{662}) \quad (2)$$
$$\text{Carotenoids} =(4.695 \times Abs_{440})-0.268\ (\text{Chl.a Chl.b}) \quad (3)$$

Where *Abs*= absorbance of sample at the indicated wave length.

Results were expressed as mg/100 g sample.

Determination of phycocyanin content (PC)

Forty mg sample was placed in a 10 ml centrifuge tube containing 100 mM phosphate buffer (10.64 g K_2HPO_4 and 5.29g KH_2PO_4 per L, pH 7.0) added and stored in refrigerator overnight after vortex. The blue supernatant was separated from the cell residue after centrifugation, and then measured by a Jenway 6705 spectrophotometer (Dunmow, Essex, UK) at 620 nm. The phycocyanin content was calculated according to (Setyoningrum & Nur, 2015) using the following equation:

$$PC(\%)=(\text{Absorbance at 620 nm} \times V\times100/\ 3{,}39\times dw) \quad (4)$$

where 3.39 is the extinction coefficient of phycocyanin at 620 nm, V is the volume of solvent and dw represents sample dry weight.

Color measurement

The color of the potato snacks was measured according to the method reported by Feng et al. (2022). A Minolta chromameter (Model CR-400; Konica Minolta Sensing Inc., Osaka, Japan) was used. Prior to color analysis, the instrument was calibrated using the manufacturer's white reference tile. Measurements were taken under D65 illumination with a 2° standard observer angle. Potato snacks samples were ground into powder by a grinder, and the color was measured. L^* is the brightness ranging from no reflection for black (L^*=0) to perfect diffuse reflection for white (L^*=100). The value "a^*" is the redness ranging from negative values for green to positive values for red. The value "b^*" is the yellowness ranging from negative values for blue and positive values for yellow.

Sensory evaluation

The potato snacks samples were evaluated in terms of taste, color, odor, texture and overall palatability by ten trained members, who voluntarily participated in the study, from Horticulture Crops Tech. Res. Dept., Food Tech. Research Institute, Agricultural Research Center, Giza, Egypt., presented in plate coded, monadic and randomly, controlled white light, at room temperature, accompanied by mineral water and the product evaluation form. A nine-point hedonic scale test was used as described by (Lawless & Heymann, 1998) on a specific scale of 9, where 1 indicated extreme dislike and 9 indicated extreme like.

Statistical Analysis

The obtained results (n = 3 biological replicates, unless otherwise stated) were statistically analyzed using one-way analysis of variance (ANOVA) under a completely randomized design. Treatment means were compared using Duncan's multiple range test with the CoStat statistical software (version 6.4, CoHort Software, USA). Differences were considered significant at $p < 0.05$ (Steel and Torrie, 1980).

Results and Discussion

Chemical composition of raw materials

The chemical composition of the raw materials, blanched potatoes sample and spirulina powder were determined and presented in Table (1). It was observed that potato sample recorded significantly higher moisture content reaching 77.50%, compared to spirulina powder which recorded as 5%. These findings are in accordance with Kaur and Aggarwal (2017) who declared that potato moisture ranged from 75.69 to 84.69%, and Rose et al. (2023) who used spirulina to fortify buttermilk and found its moisture content to be 5.12%. Meanwhile, protein, fat, crude fiber and ash contents of spirulina were recorded as 64.15, 6.61, 7.80 and 7.00%, respectively, which were significantly higher than potato sample content, for which were reached 10.04, 0.74, 6.00 and 4.00%, respectively. These findings are similar to previous studies of Riyad et al. (2020) who found that spirulina protein content was 64.48% in their evaluation of fortification of gluten-free noodles by spirulina. As mentioned by other researchers, spirulina had a protein content of 65–71%, which was higher than that of soybean and more digestible since it lacked anti-nutrients such as phytic acid and polyphenols, which are known to inhibit proteolytic enzymes (Salmeàn et al. 2015). Also, while enriching low-fat yogurt using spirulina Atallah et al. (2020) found that fat content of spirulina was 6.75%. Catana et al. (2023) reported that crude fiber in spirulina powder ranged from 5.92 to 8.86%. Spirulina provides a high concentration of easily digestible natural fibers that are beneficial to digestive health. This ease of digestion is particularly helpful for patients with intestinal malabsorption (Soni et al., 2017). Rose et al. (2023) reported that ash content of spirulina was 7.02%. Furthermore, Fang et al. (2022) and Ali et al. (2019) revealed that protein; fat, fiber and ash contents of potato were 10.24, 0.68, 5.53 and 4.19%, respectively.

Food and medical specialists have expressed an interest in phenolic compounds due to their effective antioxidant activity in vitro and in vivo, ability to scavenge free radicals and metals and inhibit radical chain reactions. Consuming phenolics has been associated with a lower risk of cancer and cardiovascular disease (Zhao & Moghadasian, 2008). The phytochemical components and antioxidant activity of potato and spirulina powder were determined and presented in Table (1). It was observed that spirulina had significantly higher TPC and DPPH values of 812 mg GAE/100g and 87.80%, respectively, while for potatoes found as 52.15 mg GAE/100g and 13%. These findings are consistent with the findings of Mesbah et al. (2022) who stated that total phenols of spirulina reached 840.60 mg GAE/100g and Rose et al. (2023) who illustrated that spirulina DPPH was 89%. On the other hand, it is noticed that potato have significantly higher carbohydrate content (79.22%) compared to spirulina (14.44%) this was higher than the carbohydrate content of potato reported by Salma et al. (2020) which was 77.16%. Hussein et al. (2021) prepared functional meal in the form of pasta rich in antioxidants and protein by fortification with various spirulina concentrations, and found that spirulina powder contained 14.81% carbohydrate. Furthermore, ascorbic acid and carotenoids content of spirulina were 178.05 and 369.00 mg/100g, respectively, significantly higher than potato with 36.49 and 0.12 mg/100g. Carotenoids are fat-soluble substances that vary in color from yellow to orange and assist both plant and microorganisms withstand damage from light exposure. Carotenoids are utilized in food in many ways, including coloring, flavoring and vitamin A supplements (Park et al., 2018). These findings are in consistence with those reported by Mohamed et al. (2021), who reported that vitamin C content of dried spirulina was 181.74 mg/100g, and Barakat et al. (2016), who prepared highly nutritious biscuit blends by adding dried spirulina and found that carotene content of spirulina powder was 310.00 mg/100g. Additionally, chlorophyll and phycocyanin were determined and results were 1530.00 mg/100g and 14.51% for spirulina powder. These results were in accordance with Riyad et al. (2020) who illustrated that chlorophyll content of spirulina powder was 1500.00 mg/100g and Sharoba (2014) who studied the physicochemical and nutritional values of different baby food formulas enriched with spirulina and revealed that phycocyanin content was 14.64% for spirulina powder. Chlorophyll, a complex green pigment produced by plants, algae, and certain bacteria, plays a vital role in the photosynthesis process by absorbing light energy and converting it into chemical energy (Björn et al., 2009).

Table 1. Chemical composition of raw materials (blanched potatoes and spirulina powder) on dry weight basis.

Constituents	Potato	Spirulina
Moisture %	77.50±0.50^{a}	5.00±1.00^{b}
Protein %	10.04±1.46^{b}	64.15±2.15^{a}
Fat %	0.74±0.04^{b}	6.61±0.11^{a}
Crude fiber %	6.00±0.20^{b}	7.80±0.30^{a}
Ash %	4.00±0.30^{b}	7.00±0.20^{a}
TPC (mg GAE/100g)	52.15±7.85^{b}	812.00±12.0^{a}
DPPH %	13.00±2.00^{b}	87.80±8.80^{a}
Carbohydrate%	79.22±2.00^{a}	14.44±2.70^{b}
Ascorbic acid (mg/100g)	36.49±0.49^{b}	178.05±8.05^{a}
Carotenoids (mg/100g)	0.12±0.07^{b}	369.00±29.00^{a}
Chlorophyll a (mg/100g)	ND	1530
Phycocyanin %	ND	14.51
Minerals Ca	48.91±6.09^{b}	709.00±9.00^{a}
(mg/100g) K	614.00±14.00^{b}	1588.00±22.00^{a}
P	344.00±14.00^{b}	1986.00±14.00^{a}
Mg	93.00±2.00^{a}	98.00±0.00^{a}
Fe	2.10±0.10^{b}	115.00±15.00^{a}

*Means (±SD) followed by different superscripts (within rows) are significantly different (p≤0.05).

Table 2. Effect of spirulina fortification on chemical composition of potato snack samples

Samples	Protein %	Fat %	Crude fiber%	Carbohydrate %
Control	9.86±0.03^{e}	0.73±0.01^{d}	5.94±0.04^{e}	79.54±0.08^{a}
PS1	10.65±0.01^{d}	0.80±0.03^{c}	6.06±0.01^{d}	78.46±0.05^{b}
PS2	11.18±0.09^{c}	0.86±0.03^{c}	6.11±0.01^{c}	77.78±0.13^{c}
PS3	11.69±0.04^{b}	0.93±0.02^{b}	6.20±0.02^{b}	77.08±0.08^{d}
PS4	12.55±0.10^{a}	1.02±0.01^{a}	6.33±0.03^{a}	75.94±0.14^{e}

*Means (±SD) followed by different superscripts (within columns) are significantly different (p≤0.05).
PS1= potato + 1.5% spirulina powder, PS2= potato +2.5% spirulina powder, PS3= potato + 3.5% spirulina powder, PS4= potato + 5% spirulina powder

Effect of spirulina fortification on chemical composition of potato snack samples.

Chemical composition of potato snacks without spirulina fortification (control) and with the fortification at varied levels of spirulina powder were determined and tabulated in Table (2). As observed the fortification with spirulina significantly increased the values for protein, fat, and crude fiber to10.65%, 0.80% and 6.06%, respectively for PS1 compared to control sample which had 9.86%, 0.73% and 5.94%, respectively, It was also observed that those values increased significantly with the increase in spirulina fortification reaching the highest values in the sample with the highest spirulina level PS4 as 12.55%, 1.02% and 6.33%, respectively. This might be due to the fact that spirulina is richer in those characteristics. These findings are similar to previous studies by Hernandez-Lopez et al. (2023) who studied the impacts of spirulina incorporation in bread prepared with four wheat flours and clarified that the protein content elevated correspondingly with the incorporation of spirulina powder. Ersyah et al. (2022) evaluated the effect of spirulina supplementation on physicochemical and sensory properties of the dry noodle and reported that there was a direct correlation between fat, fiber levels and spirulina concentration in dry noodles. On the other hand, spirulina fortification had a negative impact on carbohydrate values which was decreased to 75.94% for PS4 compared to 79.54% for control sample which might be due to lower initial carbohydrate content of spirulina powder. Addition of spirulina significantly increased the samples protein, fiber, fat and ash contents, which correspondingly mean the carbohydrate value calculated by difference would be lower. This finding is in consistance with Hussein et al. (2021) and Raczyk et al. (2022) in spirulina fortified pasta.

Effect of spirulina fortification on ash and minerals of potato snack samples

Ash and minerals (Ca, K, P, Mg and Fe) of potato snacks without spirulina (control) and with varied levels of spirulina powder were determined and data was shown in Table (4). The effect of spirulina fortification on ash and minerals content (Ca, K, P, Mg and Fe) observed in sample PS1 which recorded higher values 4.03%, 57.14, 621.78, 364.90, 92.15 and 3.77 mg/100g, respectively, compared with the control sample with 3.93%, 47.92, 607.84, 340.20, 91.96 and 2.07 mg/100g. Furthermore, the effect of different spirulina concentration on ash and minerals content could be noticed in all concentrations as they reach the maximum values in the sample with higher spirulina level (PS4) as 4.16%, 80.94, 656.86, 422.50, 92.36 and 7.62 mg/100g, respectively. These results are confirmed by Pandey et al. (2023) who studied the effect of incorporating spirulina on nutritional standards on the protein enriched vegan snack product and found that the ash increased significantly when the amount of spirulina incorporation was increased. Also, Riyad et al. (2020) stated that addition of spirulina alga to gluten free noodles led to increase in mineral contents for all samples. Similarly Pop (2022) concluded that replacing wheat flour with dried spirulina (3, 6 and 9%) increased the ash and mineral contents including Ca, K, P, Mg and Fe in all biscuit samples.

Table 3. Effect of spirulina fortification on ash and minerals of potato snack samples

Samples	Ash%	Minerals mg/100g				
		Ca	K	P	Mg	Fe
Control	3.9±0.01^{d}	47.92±0.40^{e}	607.84±1.00^{e}	340.20$^{e\pm2.20e}$	91.96±0.00^{d}	2.07±0.10^{e}
PS1	4.03±0.00^{c}	57.14±0.90^{d}	621.78±1.50^{d}	364.90^{d}±0.90^{d}	92.15±0.05^{c}	3.77±0.05^{d}
PS2	4.07±0.03^{b}	63.65±2.10^{c}	632.36±2.00^{c}	381.69±0.20^{c}	92.21±0.02^{bc}	4.74±0.08^{c}
PS3	4.10±0.02^{b}	71.17±0.70^{b}	642.16±0.80^{b}	397.81±1.10^{b}	92.27±0.03^{b}	6.02±0.07^{b}
PS4	4.16±0.01^{a}	80.94±1.90^{a}	656.86±3.10^{a}	422.50±2.00^{a}	92.36±0.03^{a}	7.62±0.12^{a}

*Means (±SD) followed by different superscripts (within columns) are significantly different (p≤0.05).
PS1= potato + 1.5% spirulina powder, PS2= potato +2.5% spirulina powder, PS3= potato + 3.5% spirulina powder, PS4= potato + 5% spirulina powder.

Table 4. Effect of spirulina fortification on antioxidant activity of potato snack samples

Samples	TPC mg GAE/100g	Ascorbic acid mg/100g	Carotenoids mg/100g	Chlorophyll a %	Phycocyanin %	DPPH %
Control	49.46±0.93^{e}	34.30±0.20^{e}	0.11±0.01^{e}	ND	ND	12.48±0.07^{e}
PS1	60.98±1.08^{d}	36.40±0.09^{d}	5.60±0.10^{d}	20.08±5.28^{d}	0.21±0.01^{d}	13.79±0.03^{d}
PS2	68.49±1.12^{c}	37.88±0.18^{c}	9.29±0.08^{c}	36.54±1.55^{c}	0.34±0.04^{c}	14.35±0.02^{c}
PS3	76.22±0.74^{b}	39.32±0.31^{b}	13.02±0.17^{b}	50.22±7.80^{b}	0.48±0.03^{b}	15.12±0.11^{b}
PS4	87.66±1.00^{a}	41.48±0.12^{a}	18.35±0.23^{a}	71.95±3.14^{a}	0.68±0.03^{a}	16.30±0.10^{a}

*Means (±SD) followed by different superscripts (within columns) are significantly different (p≤0.05).
PS1= potato + 1.5% spirulina powder, PS2= potato +2.5% spirulina powder, PS3= potato + 3.5% spirulina powder, PS4= potato + 5% spirulina powder.

Table. 5. Effect of spirulina fortification on color of potato snack samples

Samples	*L**	*a**	*b**
Control	55.21±0.08^{a}	2.88^{a}±0.02^{a}	26.98±0.07^{a}
PS1	40.85±0.04^{b}	-1.56^{b}±0.02^{b}	20.87±0.05^{b}
PS2	35.70±0.00^{c}	-2.05^{c}±0.03^{c}	19.69±0.01^{c}
PS3	35.12±0.01^{d}	-2.41^{d}±0.01^{d}	19.04±0.02^{d}
PS4	32.45±0.07^{e}	-3.20^{e}±0.02^{e}	18.00±0.04^{e}

*Means (±SD) followed by different superscripts (within columns) are significantly different (p≤0.05).
PS1= potato + 1.5% spirulina powder, PS2= potato +2.5% spirulina powder, PS3= potato + 3.5% spirulina powder, PS4= potato + 5% spirulina powder.

Effect of spirulina fortification on antioxidant activity of potato snack samples

The effect of varied concentrations of spirulina powder added to potato snack on total phenolic content (TPC), ascorbic acid, carotene, chlorophyll, phycocyanin content and DPPH activity are displayed in Table (3). It was observed that the incorporation of spirulina increased TPC, ascorbic acid, carotenoids content, chlorophyll, phycocyanin and DPPH activity significantly for PS1 sample compared to control sample content. Meanwhile, chlorophyll and phycocyanin were not detected in control sample. Moreover, the different concentrations of spirulina affected the TPC, ascorbic acid, carotene, chlorophyll, phycocyanin content and DPPH activity significantly increasing the spirulina concentration the values increased. This might be due to high initial content of these compounds in spirulina powder. These findings are in accordance with former researches by Hassanzadeh et al. (2022), Hernandez-Lopez et al. (2023) and Rose et al. (2023) who illustrated that incorporation of spirulina powder in high-protein functional drink made from pear-cantaloupe juice, bread and buttermilk significantly affected the total phenols, carotenoids and DPPH values, and that the highest values were observed in samples with the highest level of spirulina. In addition, Elshrief et al. (2022) studied enriching pasta and baked snacks with spirulina powder and stated that spirulina supplementation by 5% increased vitamin C levels in both products. Moreover, Rose et al. (2023) and Barakat et al. (2016) found that spirulina incorporation significantly improved chlorophyll and phycocyanin content in buttermilk and biscuit blends. Spirulina's effects on enhancing antioxidant activity are linked to the presence of a blue pigment called phycocyanin (Niccolai et al., 2019).

Effect of spirulina fortification on color of potato snack samples

Color parameters i.e., lightness and darkness (*L**), redness and greenness (*a**) and yellowness and blueness (*b**) of potato snacks with different concentrations of spirulina powder and control sample were determined as presented in Table (5). The data revealed that the incorporation of spirulina powder significantly decreased *L** values to 40.85 for PS1 indicating more darkness of the samples, it also resulted in a negative *a** values -1.65 for PS1 which signified that the sample tends to be greener and decreased *b** values to 20.87 for PS1 compared to control sample values which recorded 55.21, 2.88 and 26.98, respectively. By increasing the spirulina powder concentration till reaching 5% concentration, lightness (*L**) significantly decreased (32.45), with a significant green colour (-*a**) increase (-3.20) and the yellow colour (*b**) decrease (18.00). These are characteristics of the high chlorophyll, phycocyanin and carotene content in spirulina algae (Ismail et al., 2023). These findings are similar to researches provided by Mesbah et al. (2022) in yoghurt, Hernandez-Lopez et al. (2023) in bread and Tork et al. (2022) who stated that spirulina contains pigments like chlorophyll, phycocyanin, and carotene, which change all color characteristics. As a result, green was the dominant colour in samples with significant amounts of spirulina.

Figure 1. Potato snacks with spirulina fortification. (a) potato snack (control), (b) PS1=potato+1.5% spirulina powder, (c) PS2=potato +2.5% spirulina powder, (d) PS3=potato + 3.5% spirulina powder, (e) PS4=potato + 5% spirulina powder

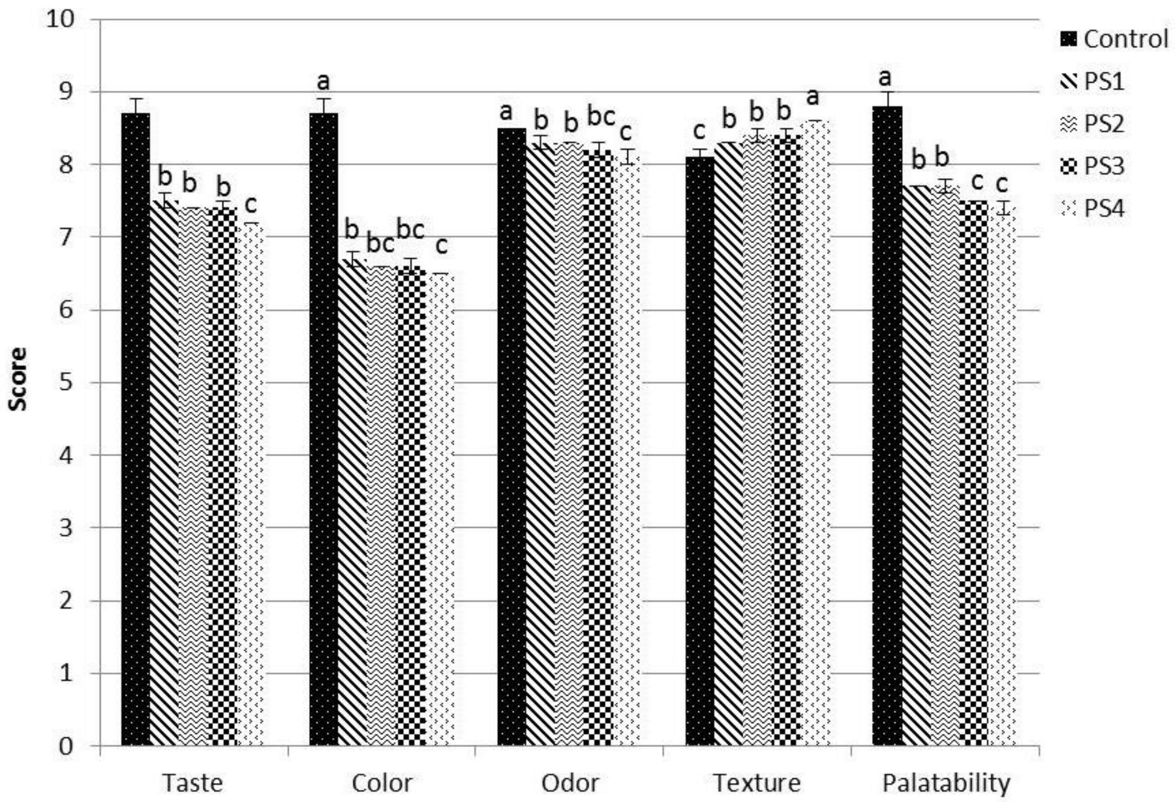

Figure 2. Effect of spirulina addition on sensory characteristics of potato snack samples.
*Different letters above bars indicate significant differences among samples within each attribute ($p \leq 0.05$). Error bars represent the standard deviation (SD). PS1= potato + 1.5% spirulina powder, PS2= potato +2.5% spirulina powder, PS3= potato + 3.5% spirulina powder, PS4= potato + 5% spirulina powder.

Effect of spirulina fortification on sensory parameters of potato snack samples

Sensory attributes have a major influence on consumer preferences (Lucas et al., 2020). The panelists evaluated the treatments' overall palatability in addition to their taste, color, odor and texture. Results are presented in Figure (1 and 2). The sensory evaluation revealed that the taste, color, odor and palatability of the spirulina enriched snacks were perceived to be significantly lower than that of the control sample. It was noticed that the panelists could find no significant ($p \leq 0.05$) difference between the samples enriched with spirulina in terms of color and odor, although the control sample scored higher acceptability in terms of color and odor than the spirulina samples scoring 8.7 and 8.5, respectively. No off odor detected from the samples containing different levels of spirulina. These results are similar to those reported by Kumar et al. (2018) in high protein nutrition bar enriched with spirulina and Riyad et al. (2020) in gluten free noodles fortified spirulina algae considering their appearance, taste, color, odor, firmness and total acceptability. Meanwhile, in terms of taste there was no significant difference between the samples enriched with spirulina (1.5, 2.5 and 3.5%) but by increasing the spirulina level to 5% there was a significant decrease in the panelists acceptance of the sample. Morsy et al. (2014) and Hassanzadeh et al. (2022) reported that higher concentration of spirulina received lower scores in taste aspect. As reported by Tork et al. (2022) samples containing spirulina at higher concentration resulted in crispier texture than the control potato chips, this finding is in line with the presented results. The panelists expressed that the spirulina enriched snacks were pleasantly crunchier than the control sample. Regarding the palatability attribute the scores were considered high for all enriched spirulina samples since the samples received scores between 7 (like moderately) and 8 (like very much). Hence, spirulina could be considered as an ingredient of potato snack to improve its protein content and nutritional value.

Conclusion

This study evaluated the physicochemical characteristics of *Spirulina platensis* and its fortification in potato snacks. Increments in protein, fat, crude fiber, antioxidants and minerals of the prepared snacks suggest that spirulina have a high potential to be used in food products to enhance their physicochemical characteristics. Chemical evaluation revealed an increase in phenolic compounds content and antioxidant activity, indicating that spirulina-enriched samples have promising functional qualities.

Sensory analysis has shown that spirulina concentrations up to 3.5% are 'moderately appreciated' by consumers. This level offers an 'optimal balance' because it significantly enhances nutritional (protein, fiber, mineral) and functional (antioxidant activity, TPC, ascorbic acid, carotenoid, chlorophyll a) properties while maintaining sensory acceptability. Future research should focus on shelf-life assessments under different storage conditions, alongside consumer studies, to validate product stability, sensory quality, and overall market acceptability.

Conflict of Interest

The author declares no conflict of interest

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