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Research article

Nectarine powder of Bulgarian origin: Physicochemical composition, antioxidant activity, microbiological and sorption characteristics

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ABSTRACT

One way to improve the quality of food products is by conducting more thorough research on regional foods. This approach has several benefits, such as promoting human health, supporting the local economy, and preserving cultural food traditions. In this regard, our study investigated the potential of nectarine powder as a regional fruit product that could be developed into a global innovation. The present study examined: the physicochemical composition, antioxidant activity, microbiological load, and adsorption and desorption characteristics of the nectarine powder. The fruit powder was acquired through the use of a heat pump dryer, where drying took place at 42 °C for a duration of 8 h until achieving a moisture content ranging from 13.5 % to 14.5 %. The approximate physicochemical values are as follows: proteins, total carbohydrates, crude fiber, ash content and total lipids. Microbiological parameters, namely the total count of mesophilic aerobic and facultative anaerobic microorganisms, yeasts and molds, *Escherichia coli*, *Salmonella* spp., coagulase-positive staphylococci, and coliforms were checked and found to be within the acceptable limits as stipulated by the relevant state standards. Antioxidant activity was demonstrated through the utilization of various methods, including DPPH (33.19 ± 0.09mMTE/g extract), ABRS (2.55 ± 0.05mMTE/g extract), FRAP (1.43 ± 0.03mMTE/g extract) and CUPRAC (0.83 ± 0.01mMTE/g extract) methods. Investigation of the mass transfer sorption characteristics is performed using the gravimetric-static method. The conditions of the experiment were selected according to the usual conditions in which the food products are found in the commercial depot. The equilibrium and monolayer moisture data are investigated at 10 °C, 25 °C and 40 °C and relative air humidity in the wide range from 11 % to 87 %, achieved by the salts saturated

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solutions. To depict the adsorption and desorption isotherms, the modified models of Halsey, Chung-Pfost, Henderson, and Oswin were selected.

1. Introduction

Nectarine (*Prunus persica)* is a type of stone fruit which is considered to originate from China and is being cultivated for thousands of years in a large part of the countries in the world [1,2]. Nectarines and peaches are from the family of the dicotyledon plants from the order of *Rosaceae,* as the nectarines are a variety of the peach but they do not have the characteristic down on their peel. Their main advantages in comparison to the peaches are: smooth, almost reflecting shining surface (skin), resembling the skin of the plumbs; sweetness with slight acidity and higher content of fibre, antioxidants, vitamin C and vitamin A. These stone fruits have a low-calorie content, ranging from approximately 44 kcal–60 kcal, and a low glycemic index. This suggests that they can be suitable for consumption by individuals with diabetes and young children [3,4]. It is established in a research of Bahrami et al. (2021) that the extracts from nectarine and peach improve the insulin secretion and the function of beta cells of the pancreas in trials with rats with diabetes [5].

It is proved that nectarines ensure benefits for the health and can be used successfully as a supplement to different foods and drinks. These fruits are frequently recommended as part of a balanced diet due to their elevated levels of antioxidants, fiber, and various vitamins and minerals, such as potassium and magnesium. Antioxidants help in the defense of the body against damage of free radicals and oxidative stress as they support healthy immune system. Fibre support digestion and regulate the blood sugar levels. Vitamins and minerals are important for the health of the human organism as a whole [6–8]. Merten et al. (2022) prove higher percentage content of diet fibre, phenolic compounds and antioxidants in adding of a different percentage of ground grain to a mixture for bread for the brewing industry (Brewer's spent grain (BSG) or draff) [9].

Dried and ground into powder nectarines can be a good addition to the daily menu in the winter months. The lack of fruit and vegetables in the daily menu can lead to different chronic diseases in adults and in growing up children [10,11].

Countries in Europe, South America, and Asia stand out as some of the major producers and exporters of nectarines in powder form. Nectarine powder is used worldwide in different productions of foods and drinks. It is a popular component in smoothies, baking dishes and light breakfasts because of its soft taste and nutritional benefits. The demand of fruit flour from nectarines is increased in the last years due to its proved healthy effect [1].

Consumption of season and regional fruits can ensure benefits as support of the local economics by their buying and use. In this way the consumers can support the local producers influencing the promotion of the local economics and the development of the country communities. The decrease of the distance which the food has to pass from the farm to the table is a way to encourage the biodiversity which influences the environment in a favourable way. The regional food systems can decrease the carbon mark and can help in dealing with climate changes. The economic support in consumption of regional season fruit can support the preservation of many cultural food traditions and practices which are important part of the region's history and heritage. The support of season models of nutrition helps and encourages the fulfilment of a healthy (balanced) diet and lowers the consumption of processed and packaged foods [12].

Nectarines are an important agricultural product in Bulgaria and they have an important role for the economics of the country. Bulgaria is one of the largest producers of nectarines in Europe, with a long history of growing and export of fruit. In the last years the Bulgarian nectarine industry is facing challenges such as an increased competition of other countries, changes in consumers' preferences and climate changing influence. Despite of all the industry remains a key factor for the Bulgarian economics and efforts for modernization and production methods improvement are exerted with the aim to guarantee its continuing success [13].

Considering the described qualities of the nectarine it is necessary an additional thorough research, affecting the creation of regimes of treatment, drying, transportation and preservation, to be carried out. The determination of sorption characteristics can afford this important information. Based on the literature's profound research and up to the moment of the writing of this manuscript, there is no available information regarding the investigation of nectarine powder of Bulgarian origin.

2. Materials and methods

2.1. Material

Nectarines of the Gergana variety were procured from various local fresh stores in Plovdiv, Bulgaria. The preparation of the sample includes: washing and drying the fruits. They are cut into small pieces such as slices until the thickness of 3.0 mm–5.0 mm and removed from the stone. The freshly sliced nectarines were arranged in a single layer on a heat pump dryer for 8 h at 42 °C or until the moisture content fell within the range of 13.5 %–14.5 %, ensuring they became thoroughly dry and brittle. After the drying process, they were finely milled with the blender (Nutribulet) into powder. Approximately 114.8 ± 11.48g of dried product was obtained from 1 kg of fresh nectarines. This preparation was carried out at the Institute of Food Preservation and Quality in Plovdiv, Bulgaria.

3. Methods

3.1. Chemical analysis (approximate composition)

The physicochemical characterization employed standardized methods as follows:

- Ash Content: Determined according to ICC Standard No. 104/1 (International Association for Cereals Science and Technology 1990) [14].
- Total Nitrogen Content: Assessed using the Kjeldahl method, with results multiplied by 6.25 to convert them to crude protein (AOAC 1990) [15].
- Total Lipids and Crude Fiber: Evaluated using standardized methods (ISO 11085:2015; ISO 5489:1981) [16,17].
- Carbohydrates: Determined by AOAC Method 988.12 (44.1.30) [18].
- Moisture Content (%): Determined by the standard method, involving the drying of 5 g of flour at 105 °C until a constant weight is achieved, following AOAC 960.39, 1990 [15].

Throughout the study, all reagents used were of analytical grade.

3.2. Antioxidant activity

To assess the antioxidant activity of nectarines, a triple extraction process was initiated using 10 mL of 70 % ethanol, conducted in a water bath at 80 °C. The resulting extract underwent filtration and subsequent drying through a rotary vacuum evaporator. The obtained extract was rehydrated in 70 % ethanol for the experimental procedure. Antioxidant activity was gauged through four distinct methods: DPPH (1,1-diphenyl-2-picrylhydrazyl radical), ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)), FRAP (Ferric Reducing Antioxidant Power Assay), and CUPRAC (CUPric Reducing Antioxidant Capacity). The methodology closely adhered to the descriptions outlined by Ivanov et al. (2014) and Bogoeva et al. (2017) [19,20].

3.3. Microbiological analysis

To confirm the microbiological safety of nectarine powder, it is necessary to carry out microbiological tests following state and international requirements, namely:

- Total Count of Mesophilic Aerobic and Facultative Anaerobic Microorganisms: In accordance with BDS EN ISO 4833–1:2013 [21];
- Yeasts and Molds: Following the guidelines of BDS EN ISO 21527–2:2011 [22];
- *Escherichia coli*: Determined according to BDS EN ISO 16649–2:2014 [23];
- *Salmonella* spp.: Complying with BDS EN ISO 6579–1:2017 [24];
- Coagulase-Positive Staphylococci: Analyzed according to BDS EN ISO 6888–1:2022 [25];
- Coliforms: Assessed as per ISO 4832:2006 [26].

Fig. 1. Hygrostat with three aluminium weighing plates and one with cristal of thymol.

3.4. Sorption characteristics

The determination of adsorption and desorption equilibrium isotherms is conducted through a gravimetric-static method [27–29]. For the analyses, the sample is prepared by placing one part in a desiccator over distilled water for the desorption process and another part of the sample in a desiccator over $CaCl_2$ for the adsorption process. After 20 days of hydration and dehydration, the powder was replaced in aluminum weighing plates and measured (1.0000g ± 0.0050g) using the analytical balance. Hygrostats (borosilicate glass jars with an acrylic plastic lid with a silicone ring) were made ready for use with saturated salt solutions derived from LiCl, CH_3COOK, $MgCl_2$, K_2CO_3, $MgNO_3$, NaBr, NaCl, KCl created conditions of the a_w from 0.1 to 0.9 (Fig. 1) [30]. Thymol crystals are placed in each hygrostat with a water activity above 0.5 to prevent microbiological growth. The weighed samples were put in the prepared jars positioned in three distinct thermostats set at temperatures of 10 °C, 25 °C, and 40 °C. They remained in these environments until reaching the equilibrium moisture content, a process that took approximately one month [31].

There are mathematical models that can predict the equilibrium moisture content (Table 1). Four modified three-parametrical model of Oswin, Ching-Pfost, Henderson and Halsey were selected for made the analyses of the obtained equilibrium sorption data [29–34].

where: M - moisture content, % d.b.; a_w - water activity, decimal; A, B and C - coefficients; t - temperature, °C [30–34].

A computer program StatSoft's *STATISTICA 12* was used to fit the modified models. They were evaluated, estimated and compared through three different criteria: the mean relative error (P%), the standard error of moisture (SEM) and the randomness of residuals (Table 2).

where: M_i and $\widehat{M}_i$ – experimentally observed and predicted by the model value of the equilibrium moisture content; N – the number of data points; A, B and C – coefficients; df – the number of degrees of freedom [30].

The monolayer moisture content is the amount of moisture that the powder can hold on its surface, at a given temperatures (10 °C, 25 °C and 40 °C) and relative air humidity from 11 % to 87 %. When the moisture content is below the monolayer level, the powder is in a dry state [30,31]. When the moisture content exceeds the monolayer level, the powder can become sticky, clump together, or even spoil. The monolayer moisture content is calculated using the linearization of the Brunauer-Emmett-Teller equation (Table 3) [35].

where: M − monolayer moisture content, % d.b.; a_w − water activity, decimal; C is the coefficient [30–35].

4. Results and discussion

4.1. Approximate composition

Results for composition of nectarine powder was expressed in a dry matter basis of 94.13 ± 0.78 %. The protein (1.98 ± 0.16 %) and total lipid (0.25 ± 0.04 %) content is low, which is a characteristic of most fruits. Controversially the total carbohydrate (86.33 ± 0.31 %) content is significantly higher but when comparing peach and nectarine or yellow and white-fleshed genotypes, there were noticeable variations in the mean sugar concentrations [36]. According to researchers, there was a strong correlation between individual sugar contents and other fruit quality characteristics. Ash content (4.87 ± 0.02 %) is closely correlated to minerals available for plants that comes through water, soil or fertilizers and varies among different plant genotypes [36,37]. Crude fiber content was 2.13 ± 0.08 %.

4.2. Antioxidant activity

Four well-known methods were used to determine antioxidant capacity - DPPH, ABTS, FRAP and CUPRAC, displayed in Table 4 and calculated on mMTE/g extract and mMTE/g dry matter basis. Nectarine powder yielded 71.60 % extract per gram.

Results vary across used methods due to different mechanisms of antioxidant reactions. Generally, fruits contain varying amounts of organic acids, phenolic compounds, flavonoids, vitamins and minerals, and all of these substances have antioxidant qualities [38]. Due to high content of polyphenols like chlorogenic acid, catechin, neochlorogenic acid, and quercetin, peaches and nectarines are excellent sources of antioxidants [39,40], which are also heavily connected to organic acids and amino acids content as well as present sugars [41]. The two main organic acids in the young fruit were malic acid and quinic acid, and these two acids favorably correlates with antioxidant capacity [42]. Furthermore, the levels of phenolic, organic acids, and carbohydrates vary considerably among the various fruit sections, with the majority of these substances being concentrated in the fruit's epidermal and sub-epidermal layers [43].

Table 1
Equations of the three-parametrical modified model.

Modified three-parametric model of	Equation	References
Oswin	$M = (A + Bt)\left(\frac{a_w}{1 - a_w}\right)^C$	[30–34]
Henderson	$1 - a_w = \exp[-A(t + B)M^C]$	[30–34]
Chung-Pfost	$a_w = \exp[\frac{-A}{t + B}\exp(-CM)]$	[30–34]
Halsey	$a_w = \exp\left[\frac{-\exp(A + Bt)}{M^C}\right]$	[30–34]

Table 2
Criteria for the suitability of the models.

Criteria	Equation	References
P, %	$P = \frac{100}{N}\sum\left|\frac{M_i - \widehat{M}_i}{M_i}\right|$	[30–34]
SEM	$SEM = \sqrt{\frac{\sum(M_i - \widehat{M}_i)^2}{df}}$	[30–34]
Randomness of residuals	$e_i = M_i - \widehat{M}_i$	[30–34]

Table 3
The Brunauer-Emmett-Teller model.

Brunauer-Emmett-Teller equation	$M = \frac{M_e C a_w}{(1-a_w)(1-a_w+Ca_w)}$	[30,31,35]

Table 4
Antioxidant activity of nectarine powder of Bulgarian origin.

Methods	mMTE/g extract	mMTE/g d.b.
DPPH	33.19 ± 0.09	23.76 ± 0.05
ABTS	2.55 ± 0.05	1.83 ± 0.01
FRAP	1.43 ± 0.03	1.03 ± 0.02
CUPRAC	0.83 ± 0.01	0.59 ± 0.02

According to some authors it seems that genetics and cultivar dependencies play a significant role in determining the fruit's phenolic content [44,45].

5. Microbiological characteristics

It is substantially important the microbiological safety of the nectarines in powder to be guaranteed due to the potential risk of food diseases. According to a research published in Journal of Food Science and Technology in 2020, the microbic safety of fruit in powder, including nectarines has a crucial significance for the prevention of diseases and infections which are carried through food. The research has established that the fruit in powder has a large potential of microbic contamination because of its high content of moisture and other nutritive substances. The authors suppose that there have to be implied proper methods of drying, preservation conditions and microbic testing with the purpose to guarantee the safety of the fruit powders [46]. In Table 5 are given the data for microbiological contamination of nectarines powder of Bulgarian origin.

The obtained results for the Total number of mesophilic aerobic and facultative anaerobic microorganisms, as well as yeasts and molds, fall within the permissible limits outlined by the applicable standards. The pathogen microorganisms - Coagulase-positive staphylococci, *Escherichia coli* и *Salmonella* spp. are not discovered during the experiment.

In conclusion, the microbiological safety of nectarines powder is of crucial importance for the research with the aim to guarantee the consumers' safety. It is important to be followed the established good hygiene practices in order to avoid contamination and to guarantee the product safety.

6. Sorption characteristics

The profound research on the sorption characteristics provide preliminary information on the stability of the food product defined by virtue of its moisture.

This knowledge contributes to the preparation of regimes of preservation (storage), treatment and transportation. Therefore, some chemical and biochemical reactions can be provoked or other microbiological reactions can be avoided. This can be achieved through controlling the moisture content in the determined proper levels received through preliminary researches on the sorption characteristics [28].

The sorption isotherms are graphically represented equilibrium, showing the connection between the product moisture with

Table 5
Microbiological parameters of nectarine powder of Bulgarian origin.

Total number of mesophilic aerobic and facultative anaerobic microorganisms, CFU/g	Yeasts and molds, CFU/g	Coliforms, CFU/g	Coagulase-positive staphylococci, CFU/g	*Escherichia coli*, CFU/g	*Salmonella* spp., absence in 25 g
$3.2\text{x}10^3$	$4.5\text{x}10^2$	1.2×10^3	<10	<10	–

determined conditions in the environment (the air temperature and relative air humidity are reported on here). The equilibrium moisture data for powdered nectarine in both adsorption and desorption processes are presented in Table 6 and Table 7. Additionally, Fig. 2 illustrates comparative sorption isotherms at 25 °C with water activity ranging from 0.1 to 0.9.

The recorded values for equilibrium moisture content in both the adsorption and desorption processes exhibit considerable variation, ranging from 9.28 % d.b. to 75.53 % d.b. For adsorption and from 9.41 % d.b. to 84.32 % d.b. For desorption. This variability underscores the high hygroscopic capacity of the product. A clear increase in the amounts is noticed in raising of a_w over 0.6. The results obtained from Tables 6 and 7 reveal a consistent trend: as the temperature increases at a constant water activity, the equilibrium moisture content decreases.

However, the keeping of high amounts of a_w is a reason for an increased development of microorganisms (bacteries, mould and yeast) and eventual flow of unwanted enzyme reactions, which is a precondition for the fast spoiling and instability of the food product. In purpose to avoid sticking (due to adsorption of moisture from the product's moisture, it is necessary the product to be preserved in low water activities [6]. Still, despite their marked hygroscopic capacity, the isotherms of the sorption do not correspond graphically to class 1st but to 2nd according to the classification by Brunauer et al. (1940) [47]. The received isotherms in adsorption and desorption have clearly marked *S*-shaped (sigmoid) non-linear shape compared to the most powdered food products [27–29].

The received data for equilibrium moisture can help in the prognosis of the optimal conditions of preservation in which the product's stability and quality are kept for the longest period. For this aim, through linearization of the model of BET, the monolayer moisture content is calculated, which indicates the quantity of the connected water in the monolayer (the layer of moisture stick to the surface) of the powder of nectarine. On Fig. 3 and on Fig. 4 are presented the linearization of the processes of adsorption and desorption at a_w from 0.1 to 0.5, as well the received coefficients for the determination of the monolayer moisture content.

The calculated amounts on the base of linearization are represented in Table 8.

Here, as well as in the amounts for equilibrium moisture, we recognize decrease in the amounts of monolayer moisture content (MMC) with increase in temperature [28]. A similar trend was observed in other examined fruit flours with a high sugar content [29]. Their high content of amorphous sugars is conductive to higher amounts of MMC and stronger hygroscopic capacity in comparison to other types of powdered products [48]. In a review, Prasantha, 2018 is summarized the reasons which provoke the high amounts of MMC in dehydrated fruit such as apples, figs, apricots, peaches, kiwi, etc. She reaches the conclusion that the behavior of the different types of fruit depends on the method of drying, their physico-chemical composition and the type of their porous structure. Consequently, each food product possesses its specific data of sorption [49].

Utilizing non-linear regression through the method of least squares, employing *STATISTICA* 12 software, and applying criteria such as P, SEM, and the distribution of residuals, it is suggested that the modified model of Halsey best describes the experimentally obtained sorption isotherms. On the base of the residues in Halsey's model it is observed their random distribution (Table 9 and Table 10).

The research conducted by Aksil et al., in 2019, focusing on the sorption characteristics of *Arbutus unedo* L. fruit powder, similarly recommends the use of the Halsey model as the most suitable for describing the sorption isotherms they obtained [29].

Nectarines are an important part of the Bulgarian economics because they are one of the main agricultural products of the country. Bulgaria is familiar with the production of nectarines with high quality which are searched in the country and abroad. Nectarines export is an important source for foreign currency for the country and the industry contributes to the common economic growth of Bulgaria. In conclusion, nectarines hold a significant place in the Bulgarian economics and society.

These analyses are a base for the creation of innovative products which can be in favor of people living in colder regions, who need a higher taking of micro- and macro-nutrients as the one containing in the powder from nectarines. In extension to this research there were made efforts to be characterized the suitability of fruit of nectarine for the production of doughy confectionary on the base of dehydrated fruit [31–34].

7. Conclusion

A comprehensive study was conducted on the ground and dried nectarines of Bulgarian origin in powder form. The study included:

Table 6
Equilibrium moisture content of nectarines powder of Bulgarian origin for the adsorption process.

	10 °C			25 °C			40 °C		
Sel	a_w	EMC[a]	SD[b]	a_w	EMC[a]	SD[b]	a_w	EMC[a]	SD[b]
LiCl	0.113	11.25	0.12	0.113	10.31	0.18	0.112	9.28	0.03
CH_3COOK	0.234	13.22	0.14	0.225	12.63	0.23	0.201	10.93	0.03
$MgCl_2$	0.335	14.90	0.17	0.328	13.44	0.03	0.316	12.23	0.15
K_2CO_3	0.431	20.21	0.09	0.432	15.83	0.07	0.432	14.67	0.16
$MgNO_3$	0.574	26.19	0.03	0.529	19.30	0.11	0.484	16.50	0.08
NaBr	0.622	30.94	0.15	0.576	19.76	0.19	0.532	18.28	0.23
NaCl	0.757	51.12	0,38	0.753	44.22	0.20	0.747	31.43	0.29
KCl	0.868	75.53	0.17	0.843	73.58	0.02	0.823	69.59	0.24

[a] Equilibrium moisture content.
[b] Standard Deviation.

Table 7
Equilibrium moisture content of nectarines powder of Bulgarian origin for the desorption process.

	10 °C			25 °C			40 °C		
Sel	a_w	EMC[a]	SD[b]	a_w	EMC[a]	SD[b]	a_w	EMC[a]	SD[b]
LiCl	0.113	12.51	0.18	0.113	10.14	0.03	0.112	9.41	0.21
CH_3COOK	0.234	13.44	0.17	0.225	12.77	0.03	0.201	12.72	0.28
$MgCl_2$	0.335	15.32	0.29	0.328	14.19	0.17	0.316	13.49	0.03
K_2CO_3	0.431	20.36	0.04	0.432	18.71	0.19	0.432	16.30	0.26
$MgNO_3$	0.574	23.48	0.02	0.529	20.04	0.15	0.484	19.17	0.19
NaBr	0.622	26.53	0.25	0.576	20.97	0.15	0.532	20.40	0.16
NaCl	0.757	54.65	0.20	0.753	46.14	0.01	0.747	45.85	0.23
KCl	0.868	84.32	0.08	0.843	69.87	0.19	0.823	63.74	0.12

[a] Equilibrium moisture content.
[b] Standard Deviation.

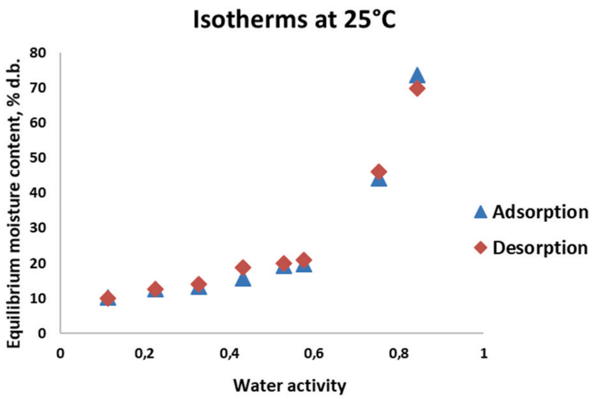

Fig. 2. Comparative graphical isotherms of nectarine powder at 25 °C.

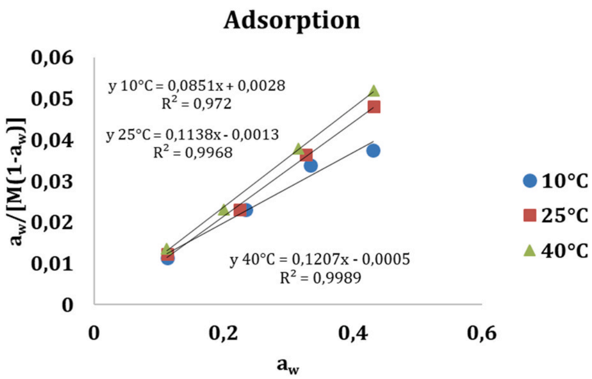

Fig. 3. The BET model for the adsorption process is linearized.

1. Results obtained for the approximate physicochemical content: 1.98 % proteins, 86.33 % total carbohydrates, 2.13 % crude fiber, 4.87 % ash content, and 0.25 % total lipids;
2. Antioxidant activity was confirmed by DPPH (33.19mMTE/g extract), ABRS (2.55mMTE/g extract), FRAP (1.43mMTE/g extract), and CUPRAC (0.83mMTE/g extract) methods;
3. The examined microbiological parameters, including the total count of mesophilic aerobic and facultative anaerobic microorganisms, yeasts and molds, *Escherichia coli*, *Salmonella* spp., coagulase-positive staphylococci, and coliforms, were found to be within the permissible limits;
4. The sorption characteristics for both adsorption and desorption processes were investigated at temperatures of 10 °C, 25 °C, and 40 °C, encompassing water activity (a_w) values within the range of 0.1–0.9;
5. Based on the linearization of the BET model, the values for monolayer moisture content were obtained for the conditions of the experiment: adsorption from 8.25 % d.b. to 11.38 % d.b. and for desorption from 9.35 % d.b. to 11.30 % d.b.;

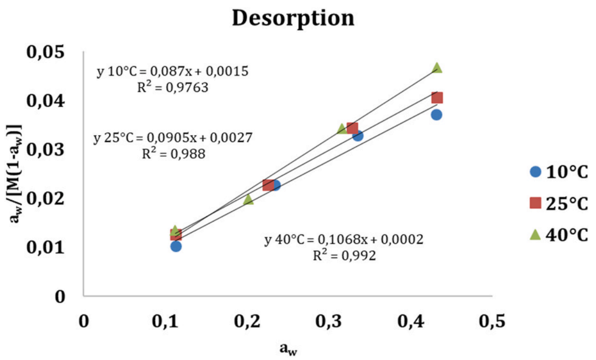

Fig. 4. The BET model for the desorption process is linearized.

Table 8
Monolayer moisture content of nectarine powder of Bulgarian origin for adsorption and desorption process.

Temperature Process	10 °C	25 °C	40 °C
Adsorption	11.38 % d.b.	8.69%d.b.	8.25 % d.b.
Desorption	11.30 % d.b.	10.73%d.b.	9.35 % d.b.

Table 9
Adsorption process: obtained coefficient of the model (A, B and C), the mean relative error (P%), the standard error of moisture content (SEM) and the randomness of residuals.

Models	A	B	C	P	SEM	Distribution of the randomness of residuals
Oswin	21.735	−0.0358	0.703	19.63	7.10	non-random
Henderson	0.000281	47.590	1.135	21.42	8.47	non-random
Chung-Pfost	298.674	0.0639	81.116	23.81	11.82	non-random
Halsey	**4.106**	**−0.0112**	**1.399**	**9.98**	**5.02**	random

Table 10
Desorption process: obtained coefficient of the model (A, B and C), the mean relative error (P%), the standard error of moisture content (SEM) and the randomness of residuals.

Models	A	B	C	P	SEM	Distribution of the randomness of residuals
Oswin	23.124	−0.0467	0.692	16.90	6.14	non-random
Henderson	0.000185	2.200	1.606	29.63	13.63	non-random
Chung-Pfost	960.054	0.0555	346.355	25.96	10.68	non-random
Halsey	**3.993**	**−0.00496**	**1.386**	**10.02**	**3.70**	random

6. The modified Halsey model has proven to be the most satisfactory description of the relation among equilibrium moisture, water activity, and temperature, accurately reflecting the characteristics observed in the obtained sorption isotherms.

Author contributions

Vasko Vasilev: Investigation. Zhivka Goranova: Investigation. Milena Temelkova: Writing – review & editing, Writing – original draft. Albena Durakova: Investigation. Adelina Lazarova Vasileva: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Milena Dimitrova-Dicheva: Investigation. Hristo Kalaydzhiev: Investigation. All authors discussed the results and contributed to the final manuscript.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Adelina Lazarova Vasileva reports administrative support and equipment, drugs, or supplies were provided by Bulgarian National Science Fund. This study was supported by the Bulgarian National Science Fund №КП-06-М47/7, project title: "Investigation of the mass transfer sorption characteristics of Bulgarian fruit powder and flour mixtures", principal investigator: Chief Assist. Prof. Adelina Lazarova Vasileva, PhD, Technical University of Sofia, branch Plovdiv, Bulgaria. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Siddiq, Peach and Nectarine. Handbook of Fruits and Fruit Processing, 2006, p. 519.
[2] D. Ravaglia, R.V. Espley, R.A. Henry-Kirk, C. Andreotti, V. Ziosi, R.P. Hellens, A.C. Allan, Transcriptional regulation of flavonoid biosynthesis in nectarine (Prunus persica) by a set of R2R3 MYB transcription factors, BMC Plant Biol. 13 (1) (2013) 1–14.
[3] D. Valero, H.M. Díaz-Mula, M. Serrano, Drying Nectarines: Functional Compounds and Antioxidant Potential, Dried Fruits, 2013, pp. 300–308.
[4] P. Drogoudi, D. Gerasopoulos, M. Kafkaletou, E. Tsantili, Phenotypic characterization of qualitative parameters and antioxidant contents in peach and nectarine fruit and changes after jam preparation, J. Sci. Food Agric. 97 (10) (2017) 3374–3383.
[5] G. Bahrami, B. Izadi, S.S. Miraghaee, B. Mohammadi, R. Hatami, S. Sajadimajd, N. Batooie, Antidiabetic potential of the isolated fractions from the plants of Rosaceae family in streptozotocin-induced diabetic rats, Research in pharmaceutical sciences 16 (5) (2021) 505.
[6] F.A. Fernandes, S. Rodrigues, C.L. Law, A.S. Mujumdar, Drying of exotic tropical fruits: a comprehensive review, Food Bioprocess Technol. 4 (2011) 163–185.
[7] F.A. Tomás-Barberán, D. Ruiz, D. Valero, D. Rivera, C. Obón, C. Sánchez-Roca, M.I. Gil, Health benefits from pomegranates and stone fruit, including plums, peaches, apricots and cherries, Bioactives in fruit: Health benefits and functional foods (2013) 125–167.
[8] D. Mihaylova, A. Popova, Z. Goranova, D. Petkova, P. Doykina, A. Lante, The perspective of nectarine fruit as a sugar substituent in puddings prepared with corn and rice starch, Foods 10 (11) (2021) 2563.
[9] D. Merten, L. Erman, G.P. Marabelli, B. Leners, Y. Ney, M.J. Nasim, T. Bohn, Potential health effects of brewers' spent grain as a functional food ingredient assessed by markers of oxidative stress and inflammation following gastro-intestinal digestion and in a cell model of the small intestine, Food Funct. 13 (9) (2022) 5327–5342.
[10] A.R. Vincente, G.A. Manganaris, C.M. Ortiz, G.O. Sozzi, C.H. Crisosto, Nutritional quality of fruits and vegetables, in: Postharvest Handling, Academic press, 2014, pp. 69–122.
[11] R.K. Hodder, F.G. Stacey, K.M. O'Brien, R.J. Wyse, T. Clinton-McHarg, F. Tzelepis, E.L. James, K.M. Bartlem, N.K. Nathan, R. Sutherland, E. Robson, S.L. Yoong, L. Wolfenden, Interventions for increasing fruit and vegetable consumption in children aged five years and under, Cochrane Database Syst. Rev. 2018 (1) (2018), https://doi.org/10.1002/14651858.CD008552.pub4.
[12] Y.H. Shin, M. Hancer, The role of attitude, subjective norm, perceived behavioral control, and moral norm in the intention to purchase local food products, J. Foodserv. Bus. Res. 19 (4) (2016) 338–351.
[13] M. Mayus, A. Alaphilippe, J. Buurma, T. Caffi, Y. Capowiez, G. Fortino, J. Strassemeyer, The database PESAP to design pomefruit protection strategies, in: Proceedings of the 8th International Conference on Integrated Fruit Production, 2013, pp. 551–555.
[14] International Association for Cereal Science and Technology, 104/1: Determination of Ash in Cereals and Cereal Products. Approved 1960, Revised 1990, International Association for Cereal Science and Technology, Vienna, Austria, 1990.
[15] AOAC. Official, Methods of Analysis 960, vol. 39, 15 th ed. Association of Official Analytical, Washington , DC, 1990.
[16] ISO 11085, Cereals, Cereals-Based Products and Animal Feeding Stuffs—Determination of Crude Fat and Total Fat Content by the Randall, extraction method, Switzerland, 2015.
[17] ISO 5489, Agricultural Food Products—Determination of Crude Fibre Content, General Method, 1981.
[18] AOAC Method 988.12 (44.1.30). Phenol-Sulfuric Acid Assay for Total Carbohydrate Determination Using Ultraviolet-Visible Range Spectroscopy (UV-Vis).
[19] I. Ivanov, R. Vrancheva, A. Marchev, N. Petkova, I. Aneva, P. Denev, A. Pavlov, Antioxidant activities and phenolic compounds in Bulgarian Fumaria species, International Journal of Current Microbiology and Applied Sciences 3 (2) (2014) 296–306.
[20] A.L. Bogoeva, A.G. Durakova, A.I. Pavlov, V.B. Yanakieva, R.Z. Vrancheva, B.V. Bozadzhiev, K.B. Choroleeva, Antioxidant activity and storage regime of defatted grape seeds flour, Wine Studies 6 (1) (2017).
[21] BDS EN ISO 4833-1, Microbiology of the Food Chain - Horizontal Method for the Enumeration of Microorganisms - Part 1: Colony Count at 30 Degrees C by the Pour Plate Technique, 2013.
[22] BDS EN ISO 21527-2, Microbiology of Food and Animal Feeding Stuffs — Horizontal Method for the Enumeration of Yeasts and Moulds — Part 2: Colony Count Technique in Products with Water Activity Less than or Equal to 0, 2011, p. 95.
[23] BDS EN ISO 16649-2, Microbiology of Food and Animal Feeding Stuffs — Horizontal Method for the Enumeration of Beta-Glucuronidase-Positive Escherichia coli — Part 2: Colony-count Technique at 44 Degrees C Using 5-Bromo-4-Chloro-3-Indolyl Beta-D-Glucuronide, 2014.
[24] BDS EN ISO 6579-1, Microbiology of the Food Chain - Horizontal Method for the Detection, Enumeration and Serotyping of Salmonella - Part 1: Detection of Salmonella Spp, 2017 (ISO 6579-1:2017).
[25] BDS EN ISO 6888-1, Microbiology of the Food Chain - Horizontal Method for the Enumeration of Coagulase-Positive Staphylococci (Staphylococcus aureus and Other Species) - Part 1: Method Using Baird-Parker Agar Medium, 2022.
[26] ISO 4832, Microbiology of Food and Animal Feeding Stuffs — Horizontal Method for the Enumeration of Coliforms — Colony-Count Technique, International Organization for Standardization, Brussels, Belgium, 2006.
[27] B.R. Prasantha, P.N.R.J. Amunogoda, Moisture adsorption characteristics of solar-dehydrated mango and jackfruit, Food Bioprocess Technol. 6 (2013) 1720–1728.
[28] N. Hidar, M. Ouhammou, A. Idlimam, A. Jaouad, M. Bouchdoug, A. Lamharrar, M. Mahrouz, Investigation of water adsorption and thermodynamic properties of stevia powder, J. Food Meas. Char. 12 (2018) 2615–2625.
[29] T. Aksil, M. Abbas, M. Trari, S. Benamara, Water adsorption on lyophilized Arbutus unedo L. fruit powder: determination of thermodynamic parameters, Microchem. J. 145 (2019) 35–41.
[30] A. Bogoeva, Sorption characteristics of flour mixtures enriched with grape seeds flour of Bulgarian and French raw materials, J. Cent. Eur. Agric. 21 (3) (2020) 609–617.

[31] A.L. Vasileva, A.G. Durakova, Sorption comparative study of nectarine powder and flour mixtures with its participation. In IOP Conference Series: earth and Environmental Science, IOP Publishing 1234 (1) (2023) 012009.
[32] A. Vasileva, A. Durakova, M. Dimitrova-Dicheva, Z. Goranova, H. Kalaydzhiev, K. Georgiev, Oat flour enriched with nectarine powder of Bulgarian origin–antioxidant activity, microbiological and moisture sorption characteristics, Bulgarian Journal of Agricultural Science 28 (6) (2022) 1147–1155.
[33] A.L. Vasileva, A. Durakova, H. Kalaydzhiev, M. Dimitrova-Dicheva, Z. Goranova, K. Georgiev, Whole wheat flour enriched with nectarine powder-antioxidant activity, microbiological and moisture sorption characteristics, Food Science and Applied Biotechnology 6 (1) (2023) 95–102.
[34] A. Vasileva, A. Durakova, K. Georgiev, H. Kalaydzhiev, M. Dimitrova-Dicheva, Z. Goranova, Einkorn (*Triticum monococcum* L.) and nectarine flour mixture-antioxidant activity, microbiological and sorption characteristics, in: BIO Web of Conferences, vol. 58, EDP Sciences, 2023.
[35] S. Brunauer, P.H. Emmett, E. Teller, Adsorption of gases in multimolecular layers, J. Am. Chem. Soc. 60 (2) (1938) 309–319.
[36] C.M. Cantín, Y. Gogorcena, M.Á. Moreno, Analysis of phenotypic variation of sugar profile in different peach and nectarine [Prunus persica(L.) Batsch] breeding progenies, J. Sci. Food Agric. 89 (11) (2009) 1909–1917, https://doi.org/10.1002/jsfa.3672.
[37] E. Kirkby, Introduction, definition and classification of nutrients, Marschner's Mineral Nutrition of Higher Plants 3 (2012) 5, https://doi.org/10.1016/b978-0-12-384905-2.00001-7.
[38] P. Orazem, F. Stampar, M. Hudina, Quality analysis of "Redhaven" peach fruit grafted on 11 rootstocks of different genetic origin in a replant soil, Food Chem. 124 (2011) 1691–1698.
[39] X. Liao, P. Greenspan, R.B. Pegg, Characterizing the phenolic constituents and antioxidant capacity of Georgia peaches, Food Chem. 271 (2019) 345–353, https://doi.org/10.1016/j.foodchem.2018.07.163.
[40] C. Guo, J. Bi, X. Li, J. Lyu, X. Wu, Y. Xu, Polyphenol metabolic diversity of Chinese peach and nectarine at thinned and ripe stages by UPLC-ESI-Q-TOF-MS combined with multivariate statistical analysis, J. Food Compos. Anal. 90 (2020) 103502, https://doi.org/10.1016/j.jfca.2020.103502.
[41] H.-R. Kim, I.-D. Kim, S.K. Dhungana, M.-O. Kim, D.-H. Shin, Comparative assessment of physicochemical properties of unripe peach (prunus persica) and Japanese apricot (prunus mume), Asian Pac. J. Trop. Biomed. 4 (2014) 97–103, https://doi.org/10.1016/s2221-1691(14)60216-1.
[42] Chongting Guo, Jinfeng Bi, Xuan Li, Jian Lyu, Mo Zhou, Xinye Wu, Antioxidant profile of thinned young and ripe fruits of Chinese peach and nectarine varieties, Int. J. Food Prop. 23 (1) (2020) 12721286, https://doi.org/10.1080/10942912.2020.1797782.
[43] M. Manzoor, F. Anwar, Z. Mahmood, M. Rashid, M. Ashraf, Variation in minerals, phenolics and antioxidant activity of peel and pulp of different varieties of peach (Prunus persicaL.) fruit from Pakistan, Molecules 17 (2012) 6491–6506.
[44] M.I. Gil, F.A. Tomás-Barberán, B. Hess-Pierce, A.A. Kader, Antioxidant capacities, phenolic compounds, carotenoids, and vitamin C contents of nectarine, peach, and plum cultivars from California, J. Agric. Food Chem. 50 (2002) 4976–4982.
[45] D. Ceccarelli, A.M. Simeone, P. Nota, M.G. Piazza, C. Fideghelli, E. Caboni, Phenolic compounds (hydroxycinnamic acids, flavan-3-ols, flavonols) profile in fruit of Italian peach varieties, Plant Biosyst. Int. J. Deal. Asp. Plant Biol. 150 (2016) 1370–1375.
[46] N. Kumar, K. Prasad, Fruit powders: microbial safety concerns and intervention strategies, J. Food Sci. Technol. 57 (2) (2020) 383–392, https://doi.org/10.1007/s13197-019-04098-w.
[47] S. Brunauer, L.S. Deming, W.E. Deming, E. Teller, On a theory of the van der Waals adsorption of gases, J. Am. Chem. Soc. 62 (7) (1940) 1723–1732.
[48] Y. Tekgül, Optimization of foaming process: drying behaviour, physicochemical, and powder properties of hot air-assisted foam-mat dried nectarine, Int. J. Food Eng. 17 (10) (2021) 815–826.
[49] B.D.R. Prasantha, Prediction of moisture adsorption characteristics of dehydrated fruits using the GAB isotherm model, Ann Agric Crop Sci 3 (1) (2018) 1–4.