

## Article

# Bioactive, Physicochemical and Sensory Properties as Well as Microstructure of Organic Strawberry Powders Obtained by Various Drying Methods

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**Abstract:** This study compared the quality of organic strawberry powders, obtained by convective drying (CD), freeze drying (FD) and spray drying (SD) methods. In the study, such analyses were performed: the content of vitamin C and polyphenols by liquid chromatography method, antioxidant activity using ABTS+• radicals, microstructure using a scanning microscope, sensory quality by profile method and the determination of the physicochemical properties. The FD powders were characterised by the highest content of vitamin C and polyphenols, obtained values were close to fresh strawberries after conversion to the dry matter content. The content of these ingredients in CD and SD powders was lower by 55%–80% for vitamin C, and 80% for the polyphenols content. Strawberry flavour was most beneficial for the FD powders, while smoothness and homogeneity of appearance were equally rated for the FD and SD powders. Strawberry powders are a concentrate source of bioactive compounds and, therefore, the FD powders should especially be mainly used as a valuable component of high-value foods, especially functional foods, while CD and SD powders can be used to enrich food with vitamin C and as a valuable natural flavour and colouring component, replacing food additives.

**Keywords:** strawberry powders; drying; bioactive compounds; organic food

## 1. Introduction

Strawberries (*Fragaria x ananassa*, D.), which belong to the Rosaceae family, are valued for their unique taste, intense red colour and juicy texture. They are classified as fruit with a high content of bioactive compounds with antioxidant, anti-inflammatory and anticancer effects. They are a source of vitamin C, the fruit containing 0.30–0.70 mg g<sup>−1</sup>, depending on the variety [1], so the consumption of a portion of about 200 g covers the need for this vitamin, which, according to the Regulation (EU) No 1169/2011 of the European Parliament and of the Council of 25 October 2011 on the provision of food information to consumers, is 80 mg [2].

Strawberries are rich in phenolic compounds such as anthocyanins, ellagitannins, flavonols, flavanols and phenolic acids [3–6]. Literature data indicate that organic fruit, including strawberries, is usually characterised by a high content of bioactive ingredients [7,8]. Numerous studies indicate a beneficial prophylactic effect of strawberries on health [4,9–12]. Animal studies indicate the anticancer potential of freeze-dried strawberries and their dried extract in relation to oral cancer [13,14]. Strawberry extract shows antioxidant properties and antiproliferative activity, inhibiting the development of cancer cells in vitro [6]. The beneficial effect of freeze-dried strawberries was also demonstrated in studies carried out in patients with oesophageal dysplasia taking 60 g/day freeze-dried strawberries for six

months [15]. In people with metabolic syndrome, a reduction in total cholesterol and LDL (low-density lipoprotein) cholesterol from taking 50 g of freeze-dried strawberry powder for 1 and 2 months has been documented [16,17].

Strawberries are seasonal, perishable, very susceptible to mechanical damage and easily spoiled. It is important to use appropriate technological operations to process them quickly after harvesting. They are frozen or processed into various types of intermediate products or preparations. Drying processes are one of the important groups of the processing methods. Dried fruit can be used in the production of a large group of food products, such as food concentrates, desserts, fruit teas, conditioners and dietary supplements. The spray drying and convective drying methods are most often used to obtain dried products, and in recent years, the freeze-drying method has become increasingly common. The dried product is obtained from juices (less often purees) using high carrier additives (maltodextrin), the quantity of the latter usually being 60% with respect to the juice [18]. Convective drying is widely used because of its low cost [19]. However, this method requires a long time, which causes significant degradation of bioactive components [20] and a colour change [21]. Another disadvantage of this method is the change in the structure of the products, due to shrinkage processes that result from changes in volume and lower humidity [22]. Sublimation drying is used to obtain dehydrated fruit and vegetables of high quality and high nutritional value, but this is an expensive and slow dehydration process [23,24]. Nevertheless, freeze-dried products are characterised by high quality and lifetime, which is related to the low temperature of the process, which runs without air, reducing oxidation reactions [25,26]. The advantage of sublimation drying is that the physical, chemical and biological properties of the raw materials are significantly preserved. The freeze-drying process is considered to cause the least loss of bioactive compounds and their antioxidant properties [25–29]. Some authors report, however, that the freeze-drying process may cause a significant reduction in the content of bioactive compounds, depending on the applied process and its conditions [6,30–32].

The available literature lacks data on the comparative analysis of the bioactive compound content and the sensory quality of strawberry powders, from both organic and conventional farms, obtained by freeze drying and convective drying methods with powders obtained by the widely used spray drying of strawberry juice. Our recent studies of fruit powders obtained from chokeberry and blackcurrant by the abovementioned methods, and additionally with the use of an innovative method of drying with simultaneous drying and grinding [33,34], showed a large variation in functional properties, bioactive ingredient content and sensory quality, depending on the method used to obtain the powders. Chokeberry and blackcurrant are among those fruits with a firm and compact texture, as opposed to berries such as strawberries—fruits with a soft, easily disintegrating texture and a much higher water content [4,35,36].

The aim of this study was to examine and compare the quality characteristics of the different powders obtained from organic strawberries, which belong to the group of berries, providing valuable bioactive ingredients with health-promoting properties, and classified as so-called ‘superfruits.’ The available literature does not contain data on the characteristics of the powders obtained from organic strawberries using various drying methods. Comparison of the content of bioactive ingredients and the sensory quality of powders obtained using different drying methods is important from both the scientific and the commercial point of view. The results of this comparison may be a valuable guideline for manufacturers to decide on the use of powders depending on their quality, i.e., in the case of powders with a high content of bioactive ingredients, their use as dietary supplements or high quality food, while in the case of those with a lower content of active compounds, their use as natural additives increasing the sensory quality, especially the taste and colour of the products. Also, the functional properties, especially the solubility and textural characteristics and the associated microstructure of the powders, are very important in determining and selecting their applicability.

## 2. Materials and Methods

### 2.1. Materials

The strawberries used for all the drying methods were of the same origin 'Honeoye.' Plants were cultivated using organic systems in a farm located in the Lublin region. The freeze-drying process was carried by using an Alpha 1–4 LSC lyophiliser (Martin Christ GmbH, Osterode am Harz, Germany) (initially frozen at  $-30\text{ }^{\circ}\text{C}$  over a time of 48 h, process pressure 10 Pa, temperature in the drying chamber  $-50\text{ }^{\circ}\text{C}$ , shelf temperature  $21\text{ }^{\circ}\text{C}$  and processing time 48 h). Convective drying was performed using an SUP-200G laboratory dryer with air circulation (Wamed Company, Warsaw, Poland) (air temperature  $70\text{ }^{\circ}\text{C}$ , time 25 h) to  $a_w < 0.3$ . After the convective or freeze-drying processes, the dried material was ground to a powder using a grinder with grinding knives (MKM 6003, Bosch, Stuttgart, Germany) to give a granulation below  $400\text{ }\mu\text{m}$ . The spray dried powders were obtained from strawberry juice with the addition of a 60% maltodextrin carrier (dextrose equivalent of DE 12) at air temperatures of  $160\text{ }^{\circ}\text{C}$  for the inlets and  $90\text{ }^{\circ}\text{C}$  for the outlets, and with a  $0.7\text{ mm}$  diameter dispersing nozzle being used (B-290, Mini Spray Dryer, Büchi, Flawil, Switzerland). Powders in a size range between  $630$  and  $315\text{ }\mu\text{m}$  were selected for analysis. Particle classification of powders was performed with the use of a vibratory sieve shaker (AS 200, RETSCH GmbH & Co., Haan, Germany).

### 2.2. Methods

The antioxidant activity in water extracts of the test material was determined by the ABTS+• (2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) diammonium salt) radical cation assay according to the modified method of Re et al. (1999) [37]. The results were given as  $\mu\text{mol TEAC}$  (Trolox Equivalent Antioxidant Capacity) in g of dry matter (d.m.) of the powder.

The content of the individual polyphenols was determined using the HPLC method described by Hallmann (2017) [38]. A weighed amount of powder ( $100\text{ mg}$ ) was put into a plastic test tube, and then  $1\text{ mL}$  of methanol containing  $1\text{ g}/100\text{ mL}$  ascorbic acid was added. The solution was mixed thoroughly by vortexing, and was incubated in an ultrasonic bath ( $15\text{ min}$  at  $30\text{ }^{\circ}\text{C}$ ). The samples were then swirled at a speed of  $5000\text{ rpm}$ . From the test tube,  $1\text{ mL}$  of extract was collected and re-swirled at a speed of  $12,000\text{ rpm}$ . An aliquot of  $500\text{ }\mu\text{L}$  of extract was taken for analysis by HPLC (high-performance liquid chromatography), and the polyphenols were all determined using the same HPLC set-up. A Synergi Fusion-RP 80i column ( $250 \times 4.60\text{ mm}$ ) was used, and elution was carried out using a gradient flow with two mobile phases: acetonitrile/deionised water at pH 3.00. The analysis time was  $36\text{ min}$ , the flow rate was  $1\text{ mL min}^{-1}$  and the wavelength range for detection was  $250\text{--}370\text{ nm}$ . Polyphenols were identified based on Fluka and Sigma Aldrich external standards. A Shimadzu HPLC (USA Manufacturing Inc., USA) was used, consisting of two LC-20AD pumps, a CMB-20A system controller, an SIL-20AC autosampler, an SPD-20AV UV/VIS detector and a CTD-20AC controller. The results are expressed in  $\mu\text{g}$  of the total content of the polyphenols  $\text{g}^{-1}\text{ d.m.}$  The assay was performed with three replicates.

The total vitamin C sample content was determined following extraction of the ascorbic acid and dehydroascorbic acid, and then reduction using dithiothreitol reagent. HPLC was performed using a UV 2487 detector, and separation was carried out by an RP Symmetry C18  $5\text{ }\mu\text{m}$   $4.6 \times 150\text{ mm}$  column at a temperature of  $25\text{ }^{\circ}\text{C}$ , while the injection volume varied between  $10\text{--}30\text{ }\mu\text{L}$ . The results were expressed in  $\text{mg}$  of vitamin C  $\text{g}^{-1}\text{ d.m.}$  of powder.

The Water Holding Capacity (WHC) was determined according to the procedure of Sudha et al. (2007) [39]. The WHC was expressed as  $\text{g water g}^{-1}\text{ d.m.}$  of powder. The Water Solubility Index (WSI) was measured using the method of Anderson et al. (1996) [40]. The results were expressed as  $\text{g}$  of the dissolved powder out of the  $\text{kg}$  of powder. The pH was measured using a Laboratory pH-meter (Elmetron CP-511). Dry matter was measured by a gravimetric method according to AOAC (2000) [41] methodology. The  $a_w$  value was measured using a manual AquaLab Water Activity Meter (Decagon Devices. Inc. Pullman, USA). The microstructure of the strawberry powders was investigated using a Quanta 200 XL series scanning electron microscope (FEI, Oregon, USA).

Computer image analysis using Visual Analyzer 400 (Alpha M.O.S., Toulouse, France) was used to instrumentally assess the colour of the powders.

The tested powder samples were placed in a measuring chamber, which controlled the lighting conditions. Upper and lower lighting was used to avoid the shadow effect on the tested samples. To take pictures, a 16 mm diameter lens, focus 0.1 m by Fujifilm (Tokyo, Japan), was used. Measurements were made using the CIE  $L^*a^*b^*$  system ( $L^*$  – brightness,  $+a^*$  – red,  $-a^*$  – green,  $+b^*$  – yellow,  $-b^*$  – blue) and RGB (R – red, G – green, B – blue).

The results of the colour analysis are given in graphs showing the share of individual colour shades to which the relevant codes are assigned. The codes correspond to the values of the colour parameters in both  $L^*a^*b^*$  and RGB space. The article presents a graphical interpretation of the results obtained in order to illustrate the differences between individual samples, and an additional table with the codes of individual colour parameters is attached to enable quantitative obtained data.

The sensory characteristics of the drinks prepared from the powder samples were determined by their Quantitative Descriptive Profile (QDP) in accordance with the regulatory procedure described in ISO PN-EN ISO 13299:2016-05 (2016) [42]. The drinks were prepared by mixing 50 g of each powder and 50 g sugar per kg of water. Nine quality parameters were selected for analytical profiling of the powder drinks. The quality parameters were: strawberry flavour, taste (sweet, sour, bitter), colour, uniformity of appearance, smoothness, powder perceptibility and overall quality. The intensity of the abovementioned parameters was assessed on an unstructured 10-point scale in contractual units (c.u.). Ratings were performed at the Laboratory of Sensory Analysis, which meets all the criteria specified in the BS EN ISO 8589:2010 (2010) [43] standard.

Statistica 13.0 (Tibco Software Inc., California, USA) software was used for all statistical processing. Analysis of variance (ANOVA) for dependent groups with the post hoc analysis of the NIR Fisher test at the significance level  $p < 0.05$  was used.

### 3. Results and Discussion

Table 1 shows the results of the physiochemical tests of the strawberry powders obtained by the freeze-dried (FD), convection drying (CD) and spray drying (SD) methods. The tested powders were characterised by their high dry matter content (d.m.) (ranging from 962.5 to 978.2 g kg<sup>-1</sup>) and correspondingly low water activity ( $a_w$ ) (ranging from 0.19 to 0.28). The low water activity is important for ensuring the microbiological stability of the powders during storage, provided that they are properly barrier packaged. An  $a_w$  value of less than 0.6 is considered acceptable for raw products since microbiological activity, including that of osmophilic yeast, is reduced [29]. The low water content of dried fruit is important not only for microbiological consideration, but also because of the difficulty of grinding it into powder when the water content is higher (viscous texture). Similarly, as in the present work, low levels of  $a_w$  were found in chokeberry and blackcurrant powders prepared by different methods [33,34]. The method by which the powders were obtained significantly influenced ( $p < 0.05$ ) their physical properties, particularly their WSI and WHC. The SD powders showed the lowest significant ( $p < 0.05$ ) water binding capacity, with the highest ( $p < 0.05$ ) water solubility index of 885.4 g kg<sup>-1</sup>, indicating that these powders can be used for the products with the instant type of matrix where particle solubility is required, for example in beverages and jellies. Given the lower solubility of FD and CD powders, they will be particularly useful in the preparation of products where particle sensitivity is indicated, for example in smoothies, cocktails and yoghurt. The higher solubility ( $p < 0.05$ ) (WSI) of FD powder as compared to CD powder could result from the difference in texture of these powders. In the investigations of Sadowska et al. (2019) [33,34] conducted on chokeberry and blackcurrant powders using the same methods as in this study, similar results were obtained with respect to WSI and WHC, taking into account the drying method used.

**Table 1.** Physicochemical characteristics of organic strawberry fruit dried by different methods.

Type of Drying	Dry Mass (g kg <sup>-1</sup> )	Water Activity	pH	WHC (g H <sub>2</sub> O g d.m. <sup>-1</sup> of Powder)	WSI (g kg <sup>-1</sup> )
FD	978.2 ± 0.3 <sup>c</sup>	0.10 ± 0.001 <sup>a</sup>	3.54 ± 0.01	2.81 ± 0.21 <sup>c</sup>	619.1 ± 3.3 <sup>b</sup>
CD	962.5 ± 3.2 <sup>a</sup>	0.27 ± 0.002 <sup>b</sup>	3.58 ± 0.02	2.36 ± 0.14 <sup>b</sup>	549.8 ± 3.4 <sup>a</sup>
SD	968.6 ± 2.5 <sup>b</sup>	0.28 ± 0.005 <sup>b</sup>	3.57 ± 0.02	1.05 ± 0.11 <sup>a</sup>	885.4 ± 4.6 <sup>c</sup>
Raw	915.5 ± 5.3 <sup>d</sup>	0.98 ± 0.005 <sup>c</sup>	3.56 ± 0.02	-	-

a–d: values marked by different letters differ significantly ( $p < 0.05$ ); FD: freeze drying, CD: convective drying, SD: spray drying.

Table 2 shows the content of bioactive components, such as vitamin C and polyphenols, and the antioxidant activity of powders obtained from organic strawberries using the FD, CD and SD methods—the latter involving spray drying of juice on a carrier, maltodextrin. The results obtained were characterised by significantly different contents of the determined components, depending on the method of obtaining the powder. Considering the content of vitamin C, it can be concluded that both the strawberry fruit and the powders obtained from them are rich sources of this vitamin. The determined content of vitamin C in organic strawberry fruit was 0.68 mg g<sup>-1</sup> (8.07 mg g<sup>-1</sup> d.m.). This value is similar to the literature data [1,44].

**Table 2.** The content of individual polyphenols (µg g<sup>-1</sup> d.m.), vitamin C (mg g<sup>-1</sup> d.m.) and antioxidant properties (µmol TEAC g<sup>-1</sup> d.m.) of raw organic strawberry and strawberries powders obtained by different methods.

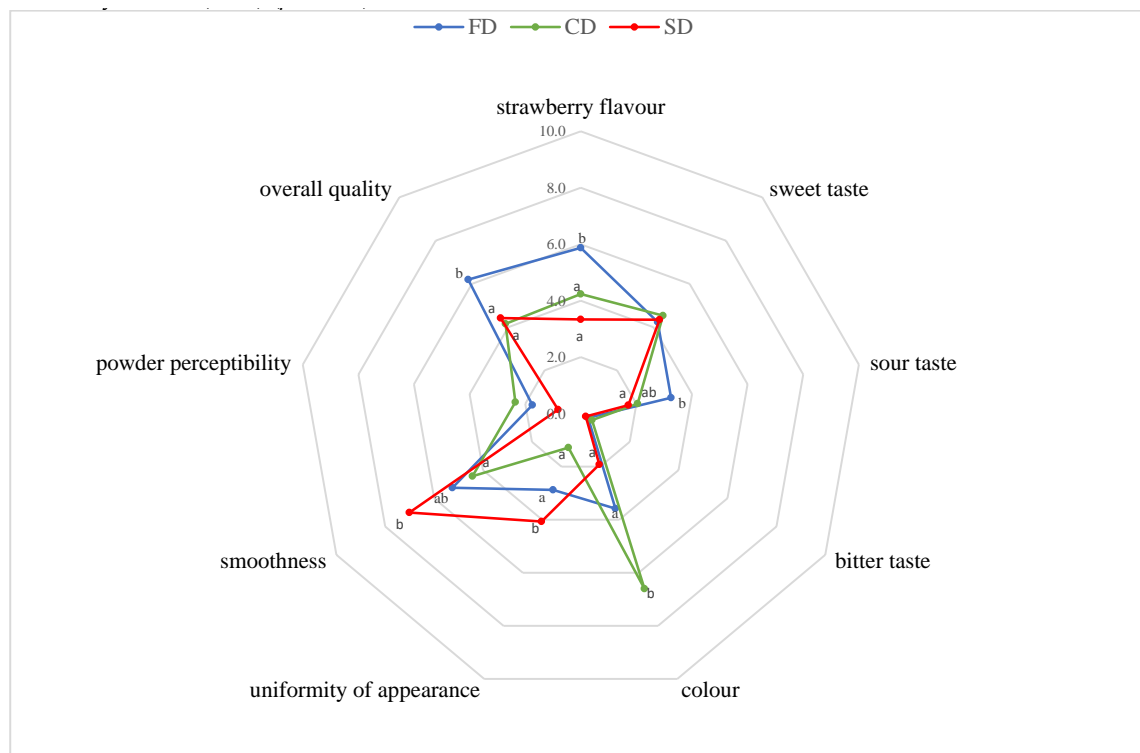
Bioactive Compounds	Raw Strawberry	FD	CD	SD
Phenolic acids				
gallic acid	691.9 ± 2.6 <sup>d</sup>	470.1 ± 17.9 <sup>c</sup>	41.5 ± 7.3 <sup>a</sup>	71.2 ± 0.4 <sup>b</sup>
chlorogenic acid	44.6 ± 0.2 <sup>c</sup>	41.5 ± 2.5 <sup>c</sup>	15.9 ± 0.5 <sup>a</sup>	30.3 ± 11.4 <sup>b</sup>
caffeic acid	175.2 ± 22.2 <sup>b</sup>	181.7 ± 21.9 <sup>b</sup>	44.3 ± 1.2 <sup>a</sup>	46.2 ± 3.1 <sup>a</sup>
<i>p</i> -coumaric acid	393.8 ± 0.4 <sup>d</sup>	357.2 ± 7.0 <sup>c</sup>	27.4 ± 0.9 <sup>a</sup>	177.7 ± 12.5 <sup>b</sup>
ferulic acid	152.7 ± 29.0 <sup>c</sup>	115.3 ± 4.0 <sup>c</sup>	6.0 ± 0.5 <sup>a</sup>	69.3 ± 6.2 <sup>b</sup>
ellagic acid	68.9 ± 0.4 <sup>c</sup>	58.5 ± 1.7 <sup>b</sup>	64.7 ± 4.3 <sup>bc</sup>	32.3 ± 1.3 <sup>a</sup>
Total phenolic acids	1527.3 ± 25.4 <sup>d</sup>	1224.3 ± 3.5 <sup>c</sup>	199.8 ± 10.9 <sup>a</sup>	427.1 ± 21.1 <sup>b</sup>
Flavonols				
quercetin-3-O-rutinoside	223.6 ± 2.4 <sup>b</sup>	179.0 ± 43.5 <sup>b</sup>	7.9 ± 1.2 <sup>a</sup>	15.7 ± 2.5 <sup>a</sup>
kaempferol-3-O-glycoside	73.4 ± 10.0 <sup>d</sup>	45.9 ± 5.5 <sup>c</sup>	30.5 ± 2.5 <sup>b</sup>	0.0 ± 0.0 <sup>a</sup>
myricetin	34.3 ± 8.00 <sup>c</sup>	30.5 ± 0.1 <sup>b</sup>	30.5 ± 0.1 <sup>b</sup>	11.7 ± 1.8 <sup>a</sup>
luteolin	26.1 ± 0.70 <sup>c</sup>	23.5 ± 0.3 <sup>b</sup>	24.8 ± 1.3 <sup>bc</sup>	9.3 ± 0.1 <sup>a</sup>
quercetin	559.0 ± 28.6 <sup>d</sup>	364.9 ± 4.3 <sup>c</sup>	309.2 ± 6.4 <sup>b</sup>	0.0 ± 0.0 <sup>a</sup>
kaempferol	37.4 ± 0.3 <sup>d</sup>	22.6 ± 0.4 <sup>c</sup>	16.9 ± 0.0 <sup>a</sup>	20.5 ± 0.2 <sup>b</sup>
quercetin-3-O-glycoside	364.9 ± 1.4 <sup>c</sup>	274.3 ± 9.2 <sup>b</sup>	254.9 ± 7.0 <sup>b</sup>	164.3 ± 10.0 <sup>a</sup>
Total flavonols	1318.9 ± 27.4 <sup>d</sup>	940.7 ± 51.7 <sup>c</sup>	674.8 ± 10.6 <sup>b</sup>	221.6 ± 10.6 <sup>a</sup>
Anthocyanins				
cyanidin-3,5-di-O-glycoside	2653.7 ± 128.1 <sup>d</sup>	2122.1 ± 5.5 <sup>c</sup>	5.4 ± 1.4 <sup>a</sup>	52.2 ± 1.2 <sup>b</sup>
pelargonidin-3,5-di-O-glycoside	605.2 ± 0.1 <sup>d</sup>	174.5 ± 0.1 <sup>b</sup>	63.3 ± 1.0 <sup>a</sup>	413.8 ± 47.4 <sup>c</sup>
pelargonidin-3,5-di-O-rutinoside	1944.9 ± 29.9 <sup>c</sup>	2100.6 ± 1.2 <sup>d</sup>	318.1 ± 22.9 <sup>b</sup>	76.7 ± 0.4 <sup>a</sup>
Total anthocyanins	5203.8 ± 126.2 <sup>d</sup>	4397.2 ± 6.6 <sup>c</sup>	386.6 ± 24.7 <sup>b</sup>	542.7 ± 11.3 <sup>a</sup>
Total flavonoids	6522.4 ± 112.2 <sup>d</sup>	5338.0 ± 58.1 <sup>c</sup>	1061.3 ± 32.4 <sup>b</sup>	764.2 ± 53.1 <sup>a</sup>
Total sum of polyphenols	8049.6 ± 113.3 <sup>c</sup>	6562.2 ± 57.5 <sup>b</sup>	1261.1 ± 42.8 <sup>a</sup>	1291.4 ± 77.4 <sup>a</sup>
Vitamin C	8.1 ± 0.5 <sup>d</sup>	7.0 ± 0.2 <sup>c</sup>	1.55 ± 0.04 <sup>a</sup>	3.22 ± 0.17 <sup>b</sup>
Antioxidant activity	525.5 ± 19.3 <sup>c</sup>	370.2 ± 8.9 <sup>b</sup>	290.1 ± 10.2 <sup>a</sup>	294.9 ± 4.8 <sup>a</sup>

a–d: values marked by different letters differ significantly ( $p < 0.05$ ); FD: freeze drying, CD: convective drying, SD: spray drying, d.m.: dry matter.



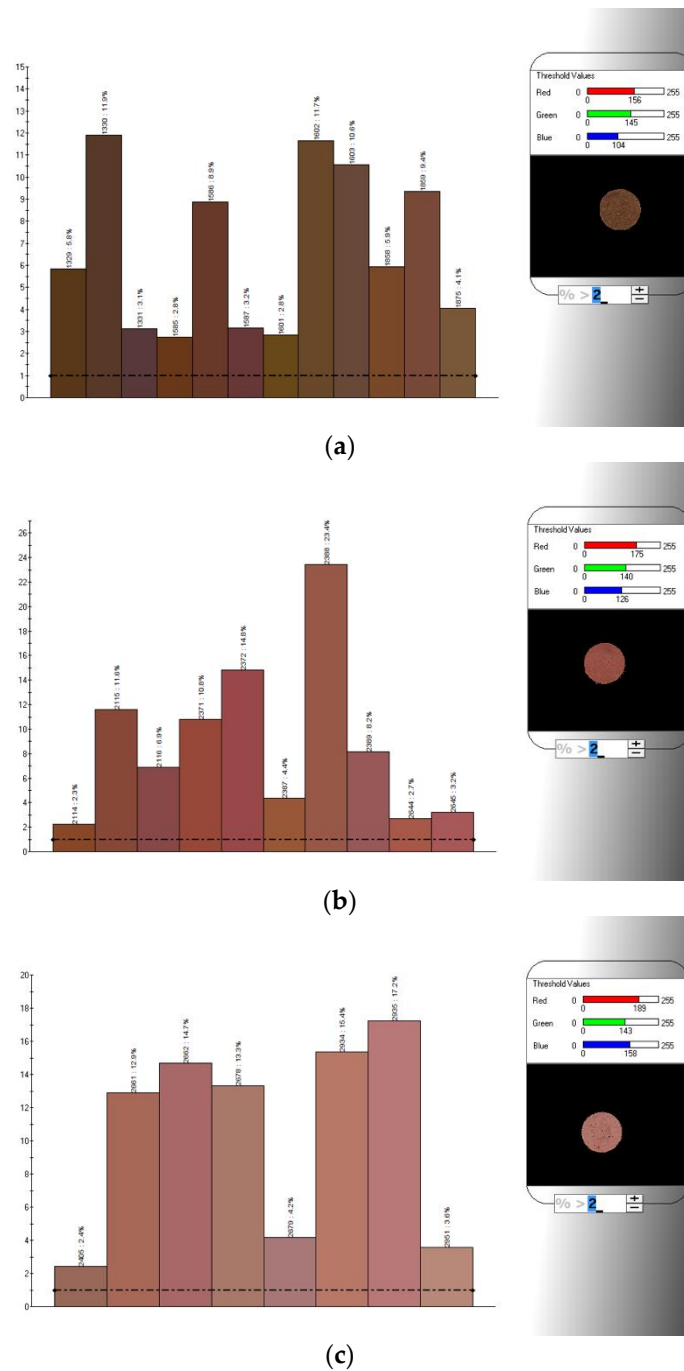
Relating the obtained values to the body's needs, it was noted that the consumption of only 100 g of strawberries, 12 g of FD powder or 25 g of CD powder covers the daily needs of an adult for this vitamin [2]. The vitamin C content in FD powders was about 14% lower than in fresh fruit, while in CD powders it was about 78% lower than in FD powders. SD powders had twice as low a content of vitamin C ( $3.2 \text{ mg g}^{-1} \text{ d.m.}$ ) as FD; however, it should be taken into account that SD powder consisted of dried juice deprived of some solid components (i.e., stones, seeds) with an additional share of the carrier, maltodextrin, which reduces the content of this compound. The literature lacks data on vitamin C losses in powders obtained from strawberries using the abovementioned methods. Earlier studies by the authors on powders obtained from chokeberry and blackcurrant showed similar relationships regarding vitamin C losses. In the case of blackcurrant powders obtained by the CD method, vitamin C losses in comparison with FD powders were significantly lower than in the case of strawberries, which may have resulted from the different chemical compositions or morphological structures of these fruits [33,34]. The tested organic strawberries were characterised by a comparable polyphenol content to those obtained in previous studies by Hallmann et al. (2016) [45]. The studied organic strawberries and the powders obtained by the FD method were characterised by a high content of phenolic compounds, among which anthocyanins, phenolic acids and flavonols dominated. Comparing the content of phenolic compounds in powders to their content in fresh fruit, it can be seen that, in terms of dry matter content, the content of these compounds, depending on their type, decreased from 18% for FD to about 85% for SD and CD. In the FD powder the total content of phenolic compounds was several times higher than in powders obtained by the SD and CD methods. Even higher differences were observed in the case of the anthocyanin content, which indicates that the use of a long-lasting convective drying process as well as spray drying causes degradation of these compounds. Given the strawberry growing system, organic and conventional, many experiments have shown that organic fruits are richer in biologically active compounds [7,8,46]. Considering the above, it can be expected that the obtained content of bioactive ingredients in the tested powders may be higher than in powders that would be obtained from fruit from the conventional system. The content of phenolic compounds and vitamin C determines the antioxidant activity of food. The freeze-drying process, followed by grinding the fruit into its powder form, did not significantly reduce the antioxidant properties of the fresh fruit. CD and SD powders were characterised by reduced, but still quite high, antioxidant activity. The obtained results are consistent with the results of previous studies by Sadowska et al. (2019) [33,34], in which powders obtained from chokeberry and blackcurrant were studied using the abovementioned methods, and additionally the fluidised-bed jet milling and drying method (FBJD).

Figure 1 shows the values of the sensory attributes obtained after evaluation of the powders prepared as beverages with added sugar. The beverages showed the greatest differences in the values obtained for strawberry flavour. The FD powders were characterised by the highest value of this discriminant. In the case of the texture characteristics, the greatest variation was achieved in the smoothness and uniformity of appearance. The greatest smoothness and the most uniform appearance were observed in beverages prepared from SD powders, which also showed the highest solubility values (WSI) ( $p < 0.05$ ).



**Figure 1.** Sensory quality of strawberry drinks prepared with FD, CD and SD powders (a–d: values marked by different letters differ significantly ( $p < 0.05$ ); FD: freeze drying, CD: convective drying, SD: spray drying).

The powders studied were characterised by a large variation in colour. CD powders had a significantly different colour, i.e., reddish-brown, in comparison to SD and FD powders, which were rated as light red. A detailed colour analysis of the powders using the instrumental method ('electronic eye') is shown in Figure 2a–c and in Table 3. Analysing the obtained results in the  $L^*a^*b^*$  colour space, it can be concluded that the SD powder had a higher value of the colour parameter  $L^*$ . This means that the sample was brighter compared to the FD and CD powders. Similar relationships were obtained for the sensory colour evaluation of the powders; the colour of the SD powder was evaluated as light red and that of the FD and CD samples as dark red. The values of parameter  $a^*$  determined for the SD powder and the FD powder were also higher as compared to the CD powder, which means that the SD and FD samples had a greater colour shift towards red. There were no major differences in the colour parameter  $b^*$  for all samples tested, which means that these samples had a similar shade of yellow. Taking into account the RGB colour model, it can be seen that the SD and FD powders showed higher R values compared to the CD powder, which indicates that the SD and FD powders had a higher saturation of red colour. The value of the colour parameter B (blue) was the highest for the SD powder, which indicates that it was more saturated with blue colour. No major differences were observed for the green colour (parameter G). The results obtained in the colour of the powders evaluated by the instrumental method and the subjective sensory evaluation show a large difference in the colour of the powders obtained by different methods. Long-lasting drying of fruit by the CD method at 70 °C caused large changes in the content of anthocyanins, providing a characteristic colour change for strawberries (light red) towards dark red (brown). The resulting differences in the colour of the powders depending on the method of preparation should be taken into account in their selection as natural food colouring additives. The CD powders were characterised by a different dark red/brown colour, as opposed to the FD and SD powders, which were light red.



**Figure 2.** Graphical interpretation of strawberry powders colour distribution using the instrumental method ('electronic eye'). (a) CD powder; (b) FD powder; (c) SD powder.

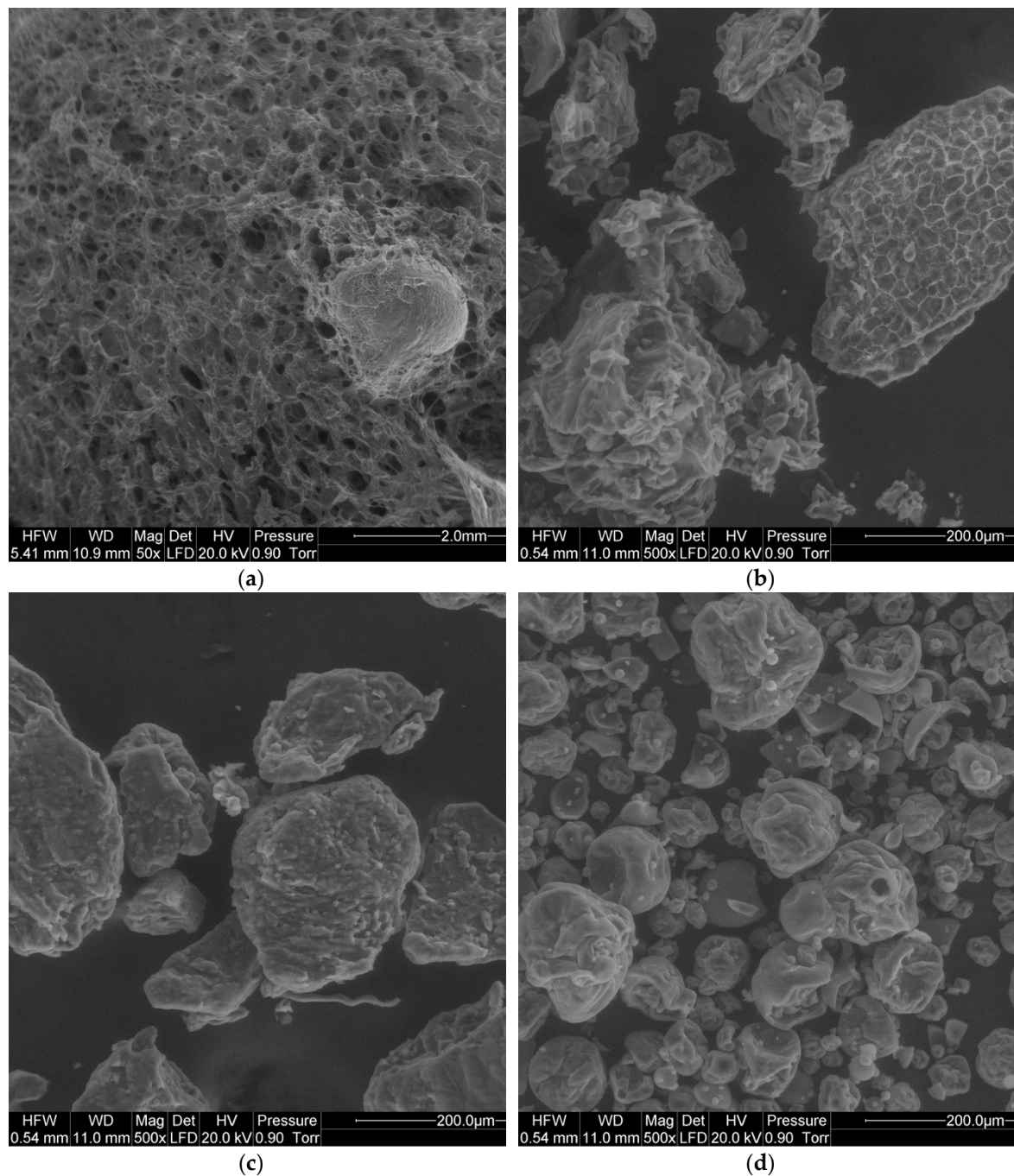


**Table 3.** Colour parameters in L\*a\*b\* and RGB space obtained for organic strawberry powders prepared by various methods (FD: freeze drying, CD: convective drying, SD: spray drying).

Colour Code	CD					
	L	a	b	R	G	B
1329	26.910	12.172	25.544	88	56	24
1330	27.116	13.189	16.120	88	56	40
1331	27.425	14.678	6.172	88	56	56
1585	29.338	19.801	28.959	104	56	24
1586	29.523	20.606	19.732	104	56	40
1587	29.800	21.795	9.880	104	56	56
1601	33.523	10.478	33.098	104	72	24
1602	33.678	11.290	24.684	104	72	40
1603	33.911	12.494	15.346	104	72	56
1858	35.894	18.738	27.913	120	72	40
1859	36.108	19.730	18.692	120	72	56
1875	40.270	10.605	23.892	120	88	56
FD						
2114	38.292	25.841	31.361	136	72	40
2115	38.487	26.666	22.278	136	72	56
2116	28.754	27.779	12.824	136	72	72
2371	41.012	33.266	26.042	152	72	56
2372	41.256	34.206	16.681	152	72	72
2387	44.550	24.855	30.223	152	88	56
2388	44.766	25.820	21.233	152	88	72
2389	45.045	27.046	12.035	152	88	88
2644	47.107	32.402	23.771	168	88	72
2645	47.366	33.460	15.637	168	88	88
SD						
2405	48.886	18.346	17.206	152	104	88
2661	50.953	25.064	20.382	168	104	88
2662	51.239	26.376	11.415	168	104	104
2678	55.089	17.797	16.653	168	120	104
2679	55.396	19.353	7.865	168	120	120
2934	57.045	24.390	19.674	184	120	104
2935	57.336	25.770	10.912	184	120	120
2951	61.180	17.318	16.183	184	136	120

In order to determine whether there is a relationship between the tested properties of the powders and their microstructure, images of their surfaces were taken with a scanning electron microscope (Figure 3). In the powders obtained from FD and CD strawberries, the original, porous structure of the fruit was largely destroyed as a result of the grinding process. This had a marked impact on the physical properties, especially WHC, which was only slightly higher in FD powders than in CD ones, where large changes occurred, deforming the texture of the fruit. In the FD powders, along with the destruction of the original spongy structure, these valuable properties of water absorption were much lower. A larger number of pores and a less firm, more easily disintegrating structure could have an impact on obtaining higher WSI values compared to the CD powders. In the SD powders, water was quickly evaporated at a high temperature with a high rotary atomiser speed, which resulted in the formation of round and oval shapes with some concavities on the surface, and multiple creases and other deformations. The solubility of the SD powders was high (WSI 885.4 g kg<sup>-1</sup>), which was a result of both the processing method and their composition (juice with the carrier). The obtained microstructure images and their relationships to the properties of strawberry powders prepared using the studied methods are similar to the results obtained in previous studies by the authors of this

paper, in which fruit powders of chokeberry and blackcurrant with a different, harder texture were tested [33,34].



**Figure 3.** Microstructure of raw strawberry and strawberry powders as shown by scanning electron microscopy (magnification 50x for raw strawberry and 500x for strawberry powders); (a) raw fruit, (b) FD powder, (c) CD powder and (d) SD powder.

#### 4. Conclusions

Powders obtained from organic strawberries by the most commonly used methods—FD, CD and SD—are characterised by significantly different bioactive component contents, antioxidant properties and physicochemical and sensory properties. Samples obtained from fruit that were freeze dried and then ground into powders had a high content of vitamin C, polyphenolic compounds and the highest

antioxidant activity, similar to raw strawberries. The SD and CD powders were characterised by 60% and 80% reduced vitamin C content, several times lower polyphenol content and significantly lower antioxidant properties, respectively. Powders obtained from strawberries, especially by the FD method, can be classified as ‘high-value foods’ due to their concentrated content of bioactive ingredients, as only 12 g of FD powder covers the body’s daily vitamin C requirement, and a small addition to the food (about 5 g per portion) authorises it to be labelled with the nutritional statement ‘high vitamin C content,’ which means that this food contains no less than 24 mg of vitamin C.

In the case of the CD and SD powders, their food addition should be 2–3 times higher to allow them being labelled with the abovementioned statement. The powders, depending on their method of preparation, had significantly different water binding capacity and solubility, determining their purpose. The WSI was the highest for the SD powders, which indicates that they can be used as ‘instant’ food components. Taking into consideration the high content of the bioactive ingredients and high operational cost of powders obtained by the FD method, these powders should be used mainly as a valuable component of high value foods and food supplements. Organic strawberry powders obtained by the CD and SD methods can also be used to enrich food with vitamin C of natural origin, but this requires 2–4 times higher addition levels compared to FD powders. These powders should primarily be widely used as natural organic food additives, replacing additional substances, including those marked with the ‘E’ symbol, and improving sensory properties, including the taste and colour of products.

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