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# Effects of Osmotic Dehydration Conditions on Iron Fortification of Beetroot (*Beta vulgaris* L.)

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**Abstract**

Although osmotic dehydration is used to enrich plant tissues with minerals, the effect of the type of iron salt, osmotic agent, and process conditions on the iron enrichment of beetroot and the quality of the dehydrated product remains unknown. In the first stage of a two-stage experiment, the effects of four iron salts (iron lactate, iron gluconate, ammonium iron citrate, and iron sulfate), used at the same mass concentration, and four osmotic substances (inulin, erythritol, xylitol, and sucrose) at concentrations of 25% and 50% on the iron content in the dehydrated material. In the second stage, the effects of temperature (20, 40, and 60 °C), process time (30, 60, and 120 min), and iron lactate concentration (0.5% and 1.0%) were evaluated using 50% solutions of inulin and erythritol. In the first stage, the highest iron contents were generally obtained in samples treated with iron lactate and iron sulfate. At an iron lactate concentration of 1.0% and a processing time of 120 min, the Fe content reached 303.59–340.84 mg/100 g of beetroot. Compared to fresh raw material, samples subjected to osmotic dehydration exhibited lower antioxidant activity, as determined by the DPPH, ABTS, and ORAC methods, as well as reduced hardness. The results indicate that osmotic dehydration may be an effective method for enriching beetroot tissue with iron. However, the practical application of the resulting material in food requires further research on safety for consumption, iron bioavailability, and sensory properties.

**Keywords:** beetroot; osmotic dehydration; iron; antioxidant activity

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## 1. Introduction

Osmotic dehydration refers to the immersion of biological materials, particularly plant products, in a hypertonic solution containing sugars, salts, or other osmotically active compounds [1,2]. The driving force of the process is the difference in chemical potential and osmotic pressure between the intracellular fluid and the surrounding solution [1,3,4]. During osmotic dehydration, three simultaneous mass-transfer phenomena occur: water is transferred from the tissue into the osmotic solution, solutes migrate from the solution into the plant matrix, and native soluble components, including organic acids, minerals, vitamins, and pigments, may leach from the tissue into the liquid phase [1–3]. A key advantage of this technology is the partial removal of water without a phase change, thereby

reducing the energy required for water evaporation and allowing the process to be conducted under relatively mild thermal conditions [1–3]. Traditionally, osmotic dehydration has been used as a food preservation method and as a pretreatment prior to convective, vacuum, or freeze-drying [2–4]. Such pretreatment can reduce the weight and volume of raw materials and lower their moisture content by approximately 30–50% [1,3]. Moreover, immersion in a hypertonic solution can reduce oxygen exposure and thereby limit polyphenol oxidase activity, enzymatic browning, and the degradation of pigments and vitamins [5,6]. More recently, osmotic dehydration has increasingly been applied in the development of functional foods [7]. The bidirectional nature of mass transfer enables the incorporation of selected bioactive compounds [8], vitamins [9], minerals [10], and even probiotic microorganisms [11] into plant tissues. Conventional sucrose-based osmotic media are increasingly being replaced or supplemented with alternative osmotic agents, including inulin and fructooligosaccharides, low-calorie polyols such as erythritol, xylitol, and maltitol, as well as concentrated fruit juices. Such approaches can contribute to the development of products with reduced energy value, prebiotic properties, or enhanced bioactive compound content [1,3,4].

Iron deficiency is one of the most prevalent nutritional deficiencies worldwide and represents a major public health concern, affecting approximately 2 billion people globally. Iron-deficiency anemia (IDA), which develops when iron depletion becomes sufficiently severe to impair hemoglobin synthesis, affects approximately 1.2 billion people worldwide [12]. Women of reproductive age and pregnant women are particularly vulnerable to iron deficiency. Other high-risk groups include patients with chronic inflammatory conditions, particularly inflammatory bowel disease, chronic kidney disease, heart failure, and cancer [13–15].

Iron plays several essential biochemical roles in the human body. It is required for the synthesis of hemoglobin and myoglobin and is involved in mitochondrial energy metabolism, oxygen transport, and the synthesis and function of several neurotransmitters [16–18]. Both non-anemic iron deficiency and iron-deficiency anemia (IDA) may be associated with fatigue, reduced exercise tolerance, irritability, depression, and impaired cognitive performance, particularly difficulties with attention, concentration, and memory [19–21]. Iron deficiency is also strongly associated with restless legs syndrome and pica [22,23].

The main causes of iron deficiency include chronic blood loss, impaired gastrointestinal absorption, and inadequate intake or low bioavailability of dietary iron [24,25]. Particular attention should be paid to individuals following plant-based diets because non-heme iron from plant sources has lower bioavailability than heme iron, although well-planned plant-based diets can provide adequate amounts of dietary iron. Once clinically relevant iron deficiency has developed, dietary modification alone is insufficient to rapidly restore depleted iron stores, and iron replacement therapy is usually required [12]. However, conventional oral iron preparations are frequently associated with gastrointestinal adverse effects, which may reduce treatment tolerability and adherence in some patients [26].

Iron enrichment of plant matrices may represent an interesting technological approach to increasing the iron content of plant-based products. Osmotic dehydration enables the incorporation of iron into beetroot (*Beta vulgaris* L.) tissue, including through the use of alternative osmotic agents such as inulin and erythritol. However, the potential use of such products in human nutrition requires an assessment of iron bioavailability and consumer safety.

The present study builds upon our previous research on the use of osmotic dehydration to enrich plant matrices with selected mineral nutrients. Earlier investigations focused on calcium enrichment of pumpkin [27] and magnesium [28] and potassium [29] enrichment of beetroot. These studies demonstrated that mineral incorporation depends on several

factors, including the chemical form of the mineral source, the osmotic agent, and the processing conditions. In the magnesium study, magnesium chloride generally produced the highest magnesium contents, despite its lower elemental magnesium proportion compared with magnesium oxide, highlighting the potential importance of aqueous solubility [28]. Similarly, potassium chloride was associated with higher potassium contents than the other potassium sources investigated, including potassium gluconate and potassium citrate [29]. However, the results obtained for magnesium and potassium cannot be directly extrapolated to iron because of differences in physicochemical properties, including the occurrence of iron in different oxidation states and its potential interactions with components of the plant matrix. Furthermore, controlling the iron content is particularly important because excessive iron intake may pose a risk to consumer health.

Previous studies have also explored the enrichment of vegetable tissues with iron. De Escalada Pla et al. [30] investigated iron fortification of pumpkin tissue by impregnation with a solution containing ferrous sulfate, followed by treatment with a hypertonic glucose-sucrose solution. The authors observed that approximately 25% of the previously incorporated iron migrated back into the osmotic solution, demonstrating that subsequent processing conditions can affect iron retention in the plant matrix. They also investigated iron release during simulated gastrointestinal digestion and reported no significant deterioration in the sensory acceptability of the iron-enriched product. However, their digestion experiments were conducted in vitro and therefore did not establish iron absorption under physiological conditions. In another study, Genevois et al. [31] used dry osmotic infusion of pumpkin with the addition of iron and ascorbic acid. The incorporation of these compounds influenced water loss and solid gain and increased changes in product color, which could be partially limited by applying an edible starch coating. In contrast to these studies, the present research investigates direct iron enrichment of beetroot tissue during immersion in iron-containing hypertonic solutions, comparing different iron salts and osmotic agents.

Four iron salts were selected for this study: iron (II) sulfate, iron (II) lactate, iron (II) gluconate, and ammonium iron (III) citrate. These compounds represent different chemical forms of iron, including Fe (II) and Fe (III) sources, and differ in their aqueous solubility and elemental iron content. Such properties may influence iron transfer from the osmotic solution into plant tissue and the final iron concentration in the product. The selected compounds correspond to iron sources listed in Annex II to Regulation (EC) No 1925/2006 concerning the addition of vitamins and minerals to foods [32]. However, inclusion of these chemical forms in the regulation does not, by itself, confirm the food-grade quality of the specific reagents used in this experiment or establish the safety of the resulting iron-enriched product.

The objective of the present study was to evaluate the effects of iron salt type, osmotic agent type and concentration, and osmotic dehydration conditions on iron incorporation into beetroot (*Beta vulgaris* L.) tissue. In the first experimental stage, four iron salts and four osmotic agents were compared, while the second stage examined the effects of treatment time, temperature, and iron (II) lactate concentration in selected inulin and erythritol solutions. The iron salts were added at the same mass concentration (1.0%), rather than at equivalent elemental iron concentrations. Therefore, the comparison was designed to evaluate iron contents obtained with equal additions of different salts, not to establish their relative incorporation efficiency at identical elemental iron doses. The study also investigated changes in antioxidant activity, proximate composition, and textural properties of the dehydrated material. The original contribution of this research lies in the combined evaluation of different iron sources, osmotic media, and processing conditions, together with selected quality characteristics of iron-enriched beetroot. This approach allows the technological effectiveness of iron enrichment to be considered alongside changes in product

quality, without assuming that high iron content alone demonstrates nutritional suitability or consumer safety.

## 2. Results and Discussion

### *2.1. Iron Content in Dehydrated Beetroot (First Stage)*

In the first stage of the study, the effects of the type of osmotic agent (inulin, xylitol, erythritol, and sucrose), its concentration (25% and 50%), and the type of iron salt (iron lactate, iron gluconate, ammonium iron citrate, and iron sulfate) on the iron content of dehydrated beetroot were evaluated before freeze-drying (Table 1). The effects of these experimental factors were further assessed using two-way factorial analysis of variance (Table 2). Iron content was also determined for the corresponding freeze-dried samples (Table 3).

**Table 1.** Iron content of osmotically dehydrated beetroot, expressed in mg/100 g of material before freeze-drying (stage 1).

| Osmotically Active Substance | Iron Lactate | Iron Gluconate | Ammonium Iron Citrate | Iron Sulfate |
|---|---|---|---|---|
| Water | 55.10 ± 2.66 $^{aB}$ | 36.46 ± 1.73 $^{aA}$ | 64.62 ± 2.91 $^{aC}$ | 73.16 ± 3.16 $^{aD}$ |
| IS25 | 182.15 ± 8.41 $^{bcB}$ | 123.37 ± 10.11 $^{cdA}$ | 178.65 ± 5.00 $^{bcdB}$ | 224.35 ± 6.70 $^{dC}$ |
| IS50 | 309.57 ± 8.99 $^{dC}$ | 195.39 ± 10.86 $^{fA}$ | 283.98 ± 15.38 $^{eBC}$ | 271.51 ± 16.79 $^{eB}$ |
| XS25 | 169.71 ± 8.69 $^{bcB}$ | 83.06 ± 8.31 $^{bA}$ | 170.55 ± 8.26 $^{bcB}$ | 153.01 ± 7.33 $^{bB}$ |
| XS50 | 244.42 ± 11.62 $^{eC}$ | 158.29 ± 10.06 $^{eA}$ | 206.80 ± 12.50 $^{dB}$ | 228.04 ± 9.99 $^{dBC}$ |
| ES25 | 193.66 ± 10.60 $^{bcB}$ | 142.88 ± 10.80 $^{deA}$ | 200.76 ± 4.93 $^{cdB}$ | 192.37 ± 3.30 $^{cB}$ |
| ES50 | 331.87 ± 22.47 $^{dC}$ | 194.42 ± 7.67 $^{fA}$ | 265.26 ± 24.42 $^{eB}$ | 311.40 ± 19.24 $^{fBC}$ |
| SS25 | 162.07 ± 3.77 $^{bC}$ | 100.87 ± 3.39 $^{bcA}$ | 157.02 ± 6.75 $^{bBC}$ | 143.42 ± 8.91 $^{bB}$ |
| SS50 | 200.83 ± 9.18 $^{cB}$ | 142.37 ± 9.64 $^{deA}$ | 157.09 ± 8.43 $^{bA}$ | 186.17 ± 5.40 $^{cB}$ |

a, b, c, d, e, f—different letters mean statistically significant differences ($p < 0.05$) between the osmotically active substances within the beetroot tested; A, B, C, D—different letters mean statistically significant differences ($p < 0.05$) between chemical forms of iron within the beetroot tested; values are means of three determinations ± SD. IS25 and IS50—inulin solution (25 and 50%); XS25 and XS50—xylitol solution (25 and 50%); ES25 and ES50—erythritol solution (25 and 50%); SS25 and SS50—sucrose solution (25 and 50%).

**Table 2.** Results of two-way factorial analysis of variance for dehydrated beetroot samples (stage 1).

| Combinations of Factors | *F* | *df* | *p* | $\eta^2$ |
|---|---|---|---|---|
| Chemical form of iron | 274.96 | 3 | 0.000000 | 0.920749 |
| Osmotically active substance | 472.51 | 8 | 0.000000 | 0.981564 |
| Chemical form of iron × Osmotically active substance | 10.05 | 24 | 0.000000 | 0.772583 |

F—statistics analysis of variance, df—degrees of freedom, *p*—level of statistical significance, $\eta^2$—effect strength.

In the samples analyzed prior to freeze-drying (Table 1), pronounced differences in iron content were observed depending on both the iron salt and the osmotic medium used. Among the iron salts tested, iron lactate and iron sulfate resulted in the highest iron contents, ranging from 162.07 to 331.87 mg/100 g and from 143.42 to 311.40 mg/100 g, respectively, across the osmotic solutions. Slightly lower values were obtained for ammonium iron citrate (157.02–283.98 mg/100 g), while the use of iron gluconate resulted in the lowest iron content (83.06–195.39 mg/100 g). In the control samples immersed in aqueous solutions containing iron salts but no osmotic agent, iron content was substantially lower, ranging from 36.46 mg/100 g for iron gluconate to 73.16 mg/100 g for iron sulfate. When interpreting the differences between the iron salts used, it should be noted that an equal mass addition

of individual compounds did not result in an equal amount of elemental iron in the osmotic solutions. Therefore, the higher Fe content in samples treated with iron lactate or iron sulfate does not constitute direct evidence of greater efficacy of these compounds when the amount of elemental iron is identical. The results obtained should be interpreted as a comparison of the enrichment effects at the same mass addition of different salts, rather than as a comparison of their relative efficiency in incorporating Fe into the tissue.

**Table 3.** Iron content of osmotically dehydrated beetroot, expressed in mg/100 g of freeze-dried material (stage 1).

| Osmotically Active Substance | Iron Lactate | Iron Gluconate | Ammonium Iron Citrate | Iron Sulfate |
|---|---|---|---|---|
| Water | 522.25 ± 25.27 $^{bcB}$ | 296.24 ± 14.04 $^{aA}$ | 586.25 ± 34.34 $^{bcdCD}$ | 650.76 ± 36.59 $^{cD}$ |
| IS25 | 593.48 ± 27.41 $^{cdB}$ | 459.93 ± 37.69 $^{bA}$ | 631.44 ± 14.52 $^{dB}$ | 705.23 ± 29.70 $^{cB}$ |
| IS50 | 691.14 ± 20.07 $^{eB}$ | 490.62 ± 27.28 $^{bcA}$ | 638.36 ± 38.24 $^{dB}$ | 688.88 ± 42.61 $^{cB}$ |
| XS25 | 520.62 ± 26.67 $^{bcB}$ | 273.43 ± 27.34 $^{aA}$ | 505.26 ± 10.55 $^{bB}$ | 464.68 ± 29.70 $^{abB}$ |
| XS50 | 449.55 ± 21.38 $^{abB}$ | 313.44 ± 19.91 $^{aA}$ | 398.11 ± 24.06 $^{aB}$ | 446.29 ± 19.55 $^{abB}$ |
| ES25 | 651.38 ± 35.65 $^{deB}$ | 534.82 ± 40.43 $^{cA}$ | 684.00 ± 16.78 $^{dB}$ | 649.31 ± 11.15 $^{cB}$ |
| ES50 | 726.94 ± 49.22 $^{eC}$ | 442.76 ± 17.46 $^{bA}$ | 605.61 ± 55.76 $^{cdB}$ | 658.42 ± 40.68 $^{cBC}$ |
| SS25 | 556.85 ± 12.97 $^{cB}$ | 340.32 ± 11.43 $^{aA}$ | 529.38 ± 22.77 $^{bcB}$ | 516.04 ± 32.06 $^{bB}$ |
| SS50 | 413.70 ± 26.71 $^{aB}$ | 271.19 ± 18.37 $^{aA}$ | 310.28 ± 16.65 $^{aA}$ | 374.67 ± 10.86 $^{aB}$ |

a, b, c, d, e—different letters mean statistically significant differences ($p < 0.05$) between the osmotically active substances within the beetroot tested; A, B, C, D—different letters mean statistically significant differences ($p < 0.05$) between chemical forms of iron within the beetroot tested; values are means of three determinations ± SD. IS25 and IS50—inulin solution (25 and 50%); XS25 and XS50—xylitol solution (25 and 50%); ES25 and ES50—erythritol solution (25 and 50%); SS25 and SS50—sucrose solution (25 and 50%).

With respect to the osmotic medium, some of the highest iron contents were obtained in inulin solutions (123.37–309.57 mg/100 g) and erythritol solutions (142.88–331.87 mg/100 g), whereas samples dehydrated in xylitol (83.06–244.42 mg/100 g) and sucrose solutions (100.87–200.83 mg/100 g) showed lower iron contents. Increasing the osmotic agent concentration from 25% to 50% promoted greater iron incorporation into beetroot tissue, although the magnitude of this effect depended on the iron salt and osmotic agent used. Among all variants analyzed prior to freeze-drying, the highest iron contents were obtained in samples dehydrated in 50% erythritol solution containing iron lactate (331.87 mg/100 g) or iron sulfate (311.40 mg/100 g), as well as in 50% inulin solution containing iron lactate (309.57 mg/100 g).

Two-way factorial analysis of variance (Table 2) confirmed that both the type of iron salt and the osmotic treatment had significant effects on iron incorporation into beetroot tissue. The strongest effect was observed for the osmotic treatment ($F = 472.51$, $p < 0.001$, $\eta^2 = 0.982$), followed by the type of iron salt ($F = 274.96$, $p < 0.001$, $\eta^2 = 0.921$). A significant interaction between these factors was also observed ($F = 10.05$, $p < 0.001$, $\eta^2 = 0.773$), indicating that the effectiveness of individual iron salts depended strongly on the osmotic conditions applied.

Table 3 summarizes the iron content of beetroot samples subjected to the same osmotic treatments and subsequently freeze-dried. On a dry-weight basis, iron content ranged from 271.19 to 726.94 mg/100 g. The highest iron content was observed in the sample dehydrated in 50% erythritol solution containing iron lactate (726.94 mg/100 g), followed by the sample treated with 25% inulin solution containing iron sulfate (705.23 mg/100 g). High iron contents were also obtained in 50% inulin solutions containing iron lactate (691.14 mg/100 g) and iron sulfate (688.88 mg/100 g), as well as in the 25% erythritol solution containing ammonium iron citrate (684.00 mg/100 g). Consistent with the results obtained prior to

freeze-drying, the lowest iron contents in the freeze-dried material were observed in samples treated with iron gluconate, particularly in 50% sucrose solution (271.19 mg/100 g) and 25% xylitol solution (273.43 mg/100 g). In the water-treated control samples, iron content after freeze-drying ranged from 296.24 to 650.76 mg/100 g. The differences between the iron content reported for samples before and after freeze-drying result from the different mass bases used to express the results. All iron content determinations were performed on the freeze-dried material, while the values for samples after osmotic dehydration but before freeze-drying were calculated based on the masses of the material measured at both stages of the process. These differences may be related both to the removal of water from plant tissue during osmotic dehydration and to the penetration of components of the osmotic solution.

### *2.2. Iron Content in Dehydrated Beetroot (Second Stage)*

In the second stage of the study, the effects of osmotic dehydration conditions on the iron content of beetroot were evaluated in detail. The investigated factors included process time (30, 60, and 120 min), temperature (20, 40, and 60 °C), iron lactate concentration (0.5% and 1.0%), and the type of osmotic agent (50% inulin, IS50, and 50% erythritol, ES50). Iron contents determined prior to freeze-drying are presented in Table 4.

**Table 4.** Iron content of osmotically dehydrated beetroot, expressed in mg/100 g of material before freeze-drying (stage 2).

| Time/Temperature | | IS50 | | ES50 | |
|---|---|---|---|---|---|
| | | **Iron Lactate 0.5%** | **Iron Lactate 1.0%** | **Iron Lactate 0.5%** | **Iron Lactate 1.0%** |
| 30 min | 20 °C | 176.76 ± 9.55 $^{aAxXY}$ | 236.00 ± 5.86 $^{aBxX}$ | 195.21 ± 8.39 $^{aAxX}$ | 287.79 ± 16.47 $^{bBxX}$ |
| | 40 °C | 169.38 ± 2.16 $^{aAxX}$ | 238.51 ± 9.05 $^{aBxX}$ | 163.04 ± 12.16 $^{aAxY}$ | 317.28 ± 22.10 $^{bBxX}$ |
| | 60 °C | 188.83 ± 4.87 $^{aAxY}$ | 227.71 ± 7.03 $^{aBxX}$ | 198.94 ± 9.72 $^{aAxX}$ | 287.19 ± 13.98 $^{bBxX}$ |
| 60 min | 20 °C | 191.01 ± 13.77 $^{aAxX}$ | 239.93 ± 12.97 $^{aBxX}$ | 215.64 ± 7.23 $^{aAxyX}$ | 339.05 ± 19.14 $^{bBxyX}$ |
| | 40 °C | 215.77 ± 14.74 $^{aAyX}$ | 257.25 ± 12.03 $^{aBxX}$ | 221.40 ± 5.29 $^{aAyX}$ | 322.44 ± 13.80 $^{bBxX}$ |
| | 60 °C | 209.43 ± 3.22 $^{aAyX}$ | 258.18 ± 19.57 $^{aBxX}$ | 224.43 ± 8.58 $^{bAxyX}$ | 316.85 ± 14.84 $^{bBxX}$ |
| 120 min | 20 °C | 226.73 ± 11.31 $^{aAyX}$ | 303.59 ± 0.78 $^{aByX}$ | 237.12 ± 17.31 $^{aAyX}$ | 325.10 ± 7.77 $^{bByX}$ |
| | 40 °C | 216.16 ± 13.48 $^{aAyX}$ | 316.14 ± 19.31 $^{aByX}$ | 241.89 ± 15.62 $^{aAyX}$ | 340.84 ± 17.04 $^{aBxX}$ |
| | 60 °C | 227.36 ± 6.31 $^{aAzX}$ | 330.07 ± 18.65 $^{aByX}$ | 230.26 ± 14.24 $^{aAyX}$ | 328.23 ± 21.60 $^{aBxX}$ |

a, b—different letters mean statistically significant differences ($p < 0.05$) between IS50 and ES50; A, B—different letters mean statistically significant differences ($p < 0.05$) between iron lactate 0.5% and 1.0%; x, y, z—different letters mean statistically significant differences ($p < 0.05$) between samples dehydrated in different time conditions (30, 60, 120 min); X, Y—different letters mean statistically significant differences ($p < 0.05$) between samples dehydrated in different temperature conditions (20, 40 and 60 °C). IS50—inulin solution (50%); ES50—erythritol solution (50%).

Samples dehydrated in solutions containing 1.0% iron lactate exhibited significantly higher iron contents than the corresponding samples treated with 0.5% iron lactate in all pairwise comparisons. Iron content ranged from 227.71 to 340.84 mg/100 g at 1.0% iron lactate and from 163.04 to 241.89 mg/100 g at 0.5%. Extending the process time promoted greater iron incorporation into beetroot tissue, although the magnitude of this effect depended on the osmotic agent, iron concentration, and temperature. The effect of temperature was less pronounced and did not show a consistent directional trend across all treatment combinations.

Among all variants analyzed prior to freeze-drying, the highest iron contents were obtained in samples dehydrated in 50% erythritol solution containing 1.0% iron lactate: 340.84 mg/100 g after 120 min at 40 °C, 339.05 mg/100 g after 60 min at 20 °C, 328.23 mg/100 g after 120 min at 60 °C, and 325.10 mg/100 g after 120 min at 20 °C. The highest iron content in beetroot dehydrated in a 50% inulin solution containing 1.0% iron

lactate was observed after 120 min at 60 °C (330.07 mg/100 g). The lowest iron contents were observed in samples treated for 30 min with 0.5% iron lactate, ranging from 163.04 to 198.94 mg/100 g.

Factorial analysis of variance (Table 5) confirmed that iron lactate concentration had the strongest effect on iron content ($F = 1116.26$, $p < 0.001$, $\eta^2 = 0.939$), followed by process time ($F = 146.44$, $p < 0.001$, $\eta^2 = 0.803$) and the type of osmotic agent ($F = 153.05$, $p < 0.001$, $\eta^2 = 0.680$). In contrast, process temperature did not exert a significant main effect ($F = 1.22$, $p = 0.302$, $\eta^2 = 0.033$), although several interactions involving temperature were statistically significant.

**Table 5.** Results of four-way factorial analysis of variance for dehydrated beetroot samples (stage 2).

| Combinations of Factors | *F* | *df* | *p* | $\eta^2$ |
|---|---|---|---|---|
| Osmotically active substance | 153.05 | 1 | 0.000000 | 0.680065 |
| Iron concentration | 1116.26 | 1 | 0.000000 | 0.939407 |
| Process time | 146.44 | 2 | 0.000000 | 0.802677 |
| Process temperature | 1.22 | 2 | 0.301959 | 0.032716 |
| Osmotically active substance × Iron concentration | 59.27 | 1 | 0.000000 | 0.451492 |
| Osmotically active substance × Process time | 12.98 | 2 | 0.000015 | 0.264950 |
| Osmotically active substance × Process temperature | 4.28 | 2 | 0.017584 | 0.106174 |
| Iron concentration × Process time | 2.44 | 2 | 0.094549 | 0.063418 |
| Iron concentration × Process temperature | 3.69 | 2 | 0.029804 | 0.092976 |
| Process time × Process temperature | 0.46 | 4 | 0.767888 | 0.024694 |
| Osmotically active substance × Iron concentration × Process time | 13.53 | 2 | 0.000010 | 0.273200 |
| Osmotically active substance × Iron concentration × Process temperature | 1.11 | 2 | 0.335236 | 0.029903 |
| Osmotically active substance × Process time × Process temperature | 2.05 | 4 | 0.095859 | 0.102413 |
| Iron concentration × Process time × Process temperature | 5.12 | 4 | 0.001090 | 0.221558 |
| Osmotically active substance × Iron concentration × Process time × Process temperature | 1.63 | 4 | 0.175974 | 0.083046 |

F—statistics analysis of variance, df—degrees of freedom, *p*—level of statistical significance, $\eta^2$—effect strength.

Analysis of variance also revealed significant two-factor interactions between the type of osmotic agent and the concentration of iron lactate, as well as between time and process temperature, and between the concentration of iron lactate and temperature. In addition, significant three-factor interactions were observed: osmotic agent × iron lactate concentration × time and iron lactate concentration × time × temperature. These results indicate that the effect of individual parameters on iron content in beetroot tissue depended on their combination. For example, after 30 min of osmotic dehydration at 40 °C, the iron content in beetroot treated with 50% inulin and 50% erythritol solutions containing 0.5% iron lactate was 169.38 and 163.04 mg/100 g, respectively. When the iron lactate concentration in the osmotic solutions was increased to 1.0%, the corresponding values reached 238.51 and 317.28 mg/100 g, respectively. This indicates that the differences between the osmotic substances depended on the concentration of iron salt used. The significance of the three-factor interaction between the type of osmotic substance, the concentration of iron lactate, and the duration of the process is also confirmed by the results obtained at 40 °C. At an iron lactate concentration of 1.0% in the osmotic solutions, extending the dehydration time from 30 to 120 min increased the iron content in beetroot tissue from 238.51 to 316.14 mg/100 g in samples treated with 50% inulin solution, whereas a smaller increase, from 317.28 to 340.84 mg/100 g, was observed in samples treated with 50% erythritol solution. However, at an iron lactate concentration of 0.5%, a greater increase in iron content was observed in

beetroot treated with erythritol solution than in samples treated with inulin solution. The effect of temperature also varied. For example, after 120 min of osmotic dehydration in a 50% inulin solution containing 1.0% iron lactate, the iron content in beetroot tissue increased with process temperature, from 303.59 mg/100 g at 20 °C to 330.07 mg/100 g at 60 °C. In contrast, in beetroot treated with a 50% erythritol solution containing 1.0% iron lactate, the highest iron content was observed at 40 °C (340.84 mg/100 g). Furthermore, after 30 min of dehydration in a 50% erythritol solution, increasing the iron lactate concentration from 0.5% to 1.0% resulted in a greater increase in the iron content of beetroot at 40 °C than at 60 °C, whereas after 120 min, the increases were similar at both temperatures. These observations highlight the importance of interactions involving temperature, iron concentration, and process duration. The results therefore indicate that the selection of osmotic dehydration parameters should take into account their combined effects, rather than solely the main effects of individual factors.

The percentage of iron incorporated into the beetroot tissue from the osmotic solution (Table 6) ranged from 9.73 to 33.67%, with higher values generally observed at lower iron lactate concentrations and longer treatment times. The highest percentage of iron incorporated into beetroot tissue from the osmotic solution was observed in samples treated with 50% erythritol solution (ES50) containing 0.5% iron lactate after 120 min at 40 °C (33.67%), followed by 120 min at 60 °C (31.93%), 60 min at 40 °C (30.13%), and 120 min at 20 °C (29.96%). Among samples treated with 50% inulin solution (IS50), the highest iron incorporation was observed after 120 min at 20 °C (25.68%). This range was comparable to that previously reported for magnesium incorporation into beetroot tissue (10.47–23.81%) and higher than that observed for calcium incorporation into pumpkin tissue (6.22–14.94%). However, direct comparison of these values should be interpreted with caution because the studies differed in plant matrix, mineral salt, osmotic medium, and processing conditions. These factors may influence mineral solubility, ion availability in the osmotic solution, and the kinetics of mineral incorporation and retention in plant tissue. Compared with potassium, for which incorporation values of 26.19–69.56% were previously observed in beetroot, the incorporation of iron and magnesium was lower. This difference may be related to differences in the physicochemical properties of the respective ions and salts, including their hydration characteristics, mobility in aqueous media, and interactions with cell-wall components. Pectic polysaccharides contain negatively charged carboxyl groups capable of interacting with metal cations; however, the strength and nature of these interactions depend on both the cation and the structural properties of the pectin. $Fe^{2+}$ ions may interact with pectic carboxyl groups and, under suitable conditions, participate in cation-mediated associations between pectin chains. In contrast, $Mg^{2+}$ is strongly hydrated and may interact more weakly with polygalacturonate. The monovalent $K^{+}$ ion has a much lower ability to promote pectin cross-linking and may therefore remain comparatively mobile within hydrated plant tissue. These differences provide a plausible explanation for the lower incorporation of iron and magnesium compared with potassium, but this interpretation remains hypothetical. The extent of mineral incorporation during osmotic dehydration depends on several interacting factors, including the concentration and solubility of the mineral salt, process time and temperature, the type and concentration of the osmotic agent, water loss from the tissue, and the structural properties of the plant matrix. It is therefore not possible, on the basis of the present results alone, to conclude that binding of $Fe^{2+}$ or $Mg^{2+}$ to pectic components in the outer tissue layers directly limited their subsequent diffusion. Confirmation of such a mechanism would require additional studies of mineral distribution and tissue microstructure, together with characterization of mineral-pectin interactions.

**Table 6.** The level of iron incorporation efficiency (%) in the analyzed samples of osmotic dehydrated beetroot.

| Time and Temperature | | IS50 | | ES50 | |
|---|---|---|---|---|---|
| | | **Iron Lactate 0.5%** | **Iron Lactate 1.0%** | **Iron Lactate 0.5%** | **Iron Lactate 1.0%** |
| 30 min | 20 °C | 17.89 ± 1.21 $^{aAxXY}$ | 9.73 ± 0.47 $^{aBxX}$ | 23.20 ± 0.73 $^{bAxX}$ | 15.72 ± 1.15 $^{bBxX}$ |
| | 40 °C | 16.41 ± 0.96 $^{aAxX}$ | 13.30 ± 0.98 $^{aBxyY}$ | 18.79 ± 1.29 $^{aAxY}$ | 18.21 ± 1.75 $^{bAxX}$ |
| | 60 °C | 19.08 ± 0.83 $^{aAxY}$ | 10.46 ± 0.85 $^{aBxX}$ | 26.03 ± 0.25 $^{bAxZ}$ | 17.33 ± 0.85 $^{bBxX}$ |
| 60 min | 20 °C | 17.68 ± 2.18 $^{aAxX}$ | 11.15 ± 1.17 $^{aBxX}$ | 23.89 ± 1.87 $^{bAxX}$ | 21.24 ± 2.35 $^{bAyX}$ |
| | 40 °C | 20.86 ± 0.45 $^{aAyXY}$ | 12.04 ± 1.03 $^{aBxX}$ | 30.13 ± 1.36 $^{bAyY}$ | 21.55 ± 1.33 $^{bBxX}$ |
| | 60 °C | 21.61 ± 1.11 $^{aAyY}$ | 11.09 ± 0.70 $^{aBxX}$ | 24.57 ± 3.01 $^{aAxX}$ | 18.80 ± 1.74 $^{bBxX}$ |
| 120 min | 20 °C | 25.68 ± 2.57 $^{aAyX}$ | 15.18 ± 0.96 $^{aByX}$ | 29.96 ± 1.63 $^{aAyX}$ | 23.74 ± 0.40 $^{bByX}$ |
| | 40 °C | 21.31 ± 1.92 $^{aAyXY}$ | 16.02 ± 2.00 $^{aByX}$ | 33.67 ± 4.35 $^{bAyX}$ | 19.79 ± 1.01 $^{bBxY}$ |
| | 60 °C | 19.02 ± 0.44 $^{aAxY}$ | 15.52 ± 1.89 $^{aByX}$ | 31.93 ± 1.05 $^{bAyX}$ | 23.29 ± 2.04 $^{bByX}$ |

a, b—different letters mean statistically significant differences ($p < 0.05$) between IS50 and ES50; A, B—different letters mean statistically significant differences ($p < 0.05$) between iron lactate 0.5% and 1.0%; x, y—different letters mean statistically significant differences ($p < 0.05$) between samples dehydrated in different time conditions (30, 60, 120 min); X, Y, Z—different letters mean statistically significant differences ($p < 0.05$) between samples dehydrated in different temperature conditions (20, 40 and 60 °C). IS50—inulin solution (50%); ES50—erythritol solution (50%).

Table 7 presents the iron content of the samples after freeze-drying. On a dry-weight basis, iron content ranged from 372.39 to 804.15 mg/100 g. The highest iron content in freeze-dried beetroot was observed in samples dehydrated in a 50% inulin solution (IS50) containing 1.0% iron lactate for 120 min at 40 °C (804.15 mg/100 g). High iron contents were also observed in beetroot samples treated with a 50% erythritol solution (ES50) containing 1.0% iron lactate for 120 min at 40 °C (777.51 mg/100 g), 20 °C (770.42 mg/100 g), and 60 °C (728.91 mg/100 g), as well as for 60 min at 20 °C (743.05 mg/100 g) and 60 °C (720.06 mg/100 g). The lowest iron content in freeze-dried beetroot was found in samples dehydrated in ES50 containing 0.5% iron lactate for 30 min at 40 °C (372.39 mg/100 g). However, when expressed per 100 g of freeze-dried beetroot (Table 7), the relationship between iron content in the product and iron lactate concentration in the osmotic solution was not consistent across all treatment combinations. For example, after 60 min of osmotic dehydration at 60 °C in a 50% inulin solution containing 0.5% iron lactate, the iron content in freeze-dried beetroot was 636.08 mg/100 g, compared with 474.52 mg/100 g in beetroot treated under the same conditions using a solution containing 1.0% iron lactate. At the same time, when calculated per 100 g of beetroot before freeze-drying, the values for the same variants were 209.43 and 258.18 mg/100 g, respectively (Table 4). The differing trends in these relationships result from the use of different reference masses when expressing the results. The iron content per 100 g of freeze-dried product depends not only on the total amount of this element in the sample but also on the amount of residual dry matter. For this reason, a higher value expressed per 100 g of lyophilisate does not necessarily indicate a higher iron content per 100 g of material after osmotic dehydration.

This study extends our previous research on the use of bidirectional mass transfer during osmotic dehydration to modify the nutritional composition of plant matrices. In earlier studies, we investigated the enrichment of pumpkin with calcium [27] and beetroot with potassium and magnesium [28,29]. The present results demonstrate that osmotic dehydration can also be effectively used to incorporate iron into beetroot tissue. As observed in our previous studies on calcium enrichment of pumpkin and potassium and magnesium enrichment of beetroot, the concentration of the mineral salt added to the osmotic solution was an important factor determining the mineral content of the plant tissue.

**Table 7.** Iron content of osmotically dehydrated beetroot, expressed in mg/100 g of freeze-dried material (stage 2).

| Time and Temperature | | IS50 | | ES50 | |
|---|---|---|---|---|---|
| | | **Iron Lactate 0.5%** | **Iron Lactate 1.0%** | **Iron Lactate 0.5%** | **Iron Lactate 1.0%** |
| 30 min | 20 °C | 435.38 ± 23.53 $^{aAxX}$ | 544.41 ± 13.52 $^{aBxX}$ | 410.96 ± 17.66 $^{aAxX}$ | 559.47 ± 32.03 $^{aBxX}$ |
| | 40 °C | 401.13 ± 5.10 $^{aAxX}$ | 537.01 ± 20.38 $^{aBxX}$ | 372.39 ± 27.76 $^{aAxX}$ | 663.25 ± 46.21 $^{bBxY}$ |
| | 60 °C | 535.32 ± 13.80 $^{aAxY}$ | 418.85 ± 12.93 $^{aBxY}$ | 421.95 ± 20.62 $^{bAxX}$ | 656.34 ± 21.95 $^{bBxY}$ |
| 60 min | 20 °C | 397.42 ± 28.65 $^{aAxX}$ | 423.95 ± 22.92 $^{aAyXY}$ | 481.99 ± 16.17 $^{bAyXY}$ | 743.05 ± 41.96 $^{bByX}$ |
| | 40 °C | 522.82 ± 35.71 $^{aAyY}$ | 399.32 ± 18.68 $^{aByX}$ | 454.02 ± 10.85 $^{bAyX}$ | 696.82 ± 29.82 $^{bBxyX}$ |
| | 60 °C | 636.08 ± 9.79 $^{aAyZ}$ | 474.52 ± 35.97 $^{aBxY}$ | 508.94 ± 19.47 $^{bAyY}$ | 720.06 ± 33.73 $^{bBxX}$ |
| 120 min | 20 °C | 534.07 ± 26.65 $^{aAyX}$ | 555.89 ± 1.42 $^{aAxX}$ | 528.53 ± 38.58 $^{aAyX}$ | 770.42 ± 18.41 $^{bByX}$ |
| | 40 °C | 448.47 ± 27.97 $^{aAxY}$ | 804.15 ± 49.12 $^{aBzY}$ | 538.57 ± 34.78 $^{bAzX}$ | 777.51 ± 38.87 $^{aByX}$ |
| | 60 °C | 495.71 ± 13.76 $^{aAzXY}$ | 560.34 ± 31.66 $^{aByX}$ | 497.29 ± 30.75 $^{aAyX}$ | 728.91 ± 47.98 $^{bBxX}$ |

a, b—different letters mean statistically significant differences ($p < 0.05$) between IS50 and ES50; A, B—different letters mean statistically significant differences ($p < 0.05$) between iron lactate 0.5% and 1.0%; x, y, z—different letters mean statistically significant differences ($p < 0.05$) between samples dehydrated in different time conditions (30, 60, 120 min); X, Y, Z—different letters mean statistically significant differences ($p < 0.05$) between samples dehydrated in different temperature conditions (20, 40 and 60 °C). IS50—inulin solution (50%); ES50—erythritol solution (50%).

In this study, increasing the iron lactate concentration from 0.5% to 1.0% led to a statistically significant increase in iron content in all corresponding variants when the results were expressed per 100 g of beetroot after osmotic dehydration and before freeze-drying (Table 4). The range of iron content increased from 163.04–241.89 mg/100 g to 227.71–340.84 mg/100 g. A four-way factorial analysis of variance confirmed that the concentration of iron lactate had the strongest main effect among the process factors studied ($F = 1116.26$; $p < 0.001$; $\eta^2 = 0.939$). It should be emphasized, however, that this relationship was observed for results expressed on a material weight basis prior to freeze-drying and cannot be directly applied to all values presented on a per 100 g freeze-dried product basis. This trend is consistent with our previous observations for potassium, for which treatment with 5.0% KCl resulted in concentrations of 3431.39–5779.03 mg/100 g compared with 2477.18–4556.32 mg/100 g at 2.5% KCl; for magnesium, for which values of 416.33–678.91 mg/100 g were obtained at 5.0% $MgCl_2$ compared with 156.57–355.92 mg/100 g at 2.5%; and for calcium, for which concentrations of 622.8–1380.4 mg/100 g were obtained at 5.0% calcium salt compared with 349.5–747.7 mg/100 g at 2.5%.

However, the results obtained indicate that, with regard to iron fortification of beetroot, maximizing the iron content should not be the sole criterion for optimizing the process. Despite the use of relatively low concentrations of iron lactate (0.5% and 1.0%), very high levels of this component were found in the plant tissue. The significance of this issue is confirmed by a comparison of the obtained results with reference values for iron intake. The recommended daily intake of this element is 8 mg for adult men and 18 mg for women aged 19–50, while the tolerable upper intake level (UL) has been set at 45 mg/day [33]. In 2024, the EFSA indicated a safe level of total iron intake for adults of 40 mg/day, without establishing a formal UL [34]. With the highest measured iron content of 340.84 mg/100 g of the product after osmotic dehydration, a 10 g serving would provide approximately 34.1 mg of Fe, while a 15 g serving would provide approximately 51.1 mg of Fe. These findings indicate that even small servings of the fortified product could provide iron amounts substantially exceeding the recommended daily allowances. Furthermore, consumption of a 15 g serving alone would exceed both the tolerable upper intake level of 45 mg/day established by the US Food and Nutrition Board and the safe level of total iron intake of 40 mg/day proposed by EFSA, highlighting the importance of considering total dietary

iron exposure when optimizing the fortification process. Excessive iron intake can cause gastrointestinal symptoms, while long-term iron overload can lead to organ failure, particularly of the liver [34]. It should be emphasized, however, that the measured iron content is not equivalent to the amount absorbed by the human body, and its bioavailability was not assessed in this study. When evaluating the usefulness of osmotic dehydration, one must consider not only the iron content but also changes in the other properties of the product. In this study, iron enrichment was accompanied by a decrease in antioxidant activity and changes in texture. Therefore, the variant leading to the greatest accumulation of iron may not be the most advantageous in terms of overall product quality. The selection of appropriate process parameters should therefore take into account both a controlled level of iron fortification and the preservation of the antioxidant, textural, and other quality characteristics of the product.

De Escalada Pla et al. [30] also investigated the possibility of using vegetable tissue to enrich foods with iron. They impregnated pumpkin with a solution of iron (II) sulfate and then treated the material with a hypertonic solution of glucose and sucrose. The authors demonstrated that, upon exposure to the osmotic solution, approximately 25% of the previously introduced iron was reabsorbed into the solution. In a simulated digestion study using pepsin, pancreatin, and bile salts, the release of iron from pumpkin tissue was observed, indicating high iron bioaccessibility under simulated gastrointestinal conditions. At the same time, iron fortification did not cause a significant deterioration in the sensory properties of the product, including its taste and overall acceptability. In turn, Genevois et al. [31] demonstrated that impregnating pumpkin with iron and ascorbic acid affected the mass exchange process and caused changes in the color of the product, which could be partially mitigated by applying a starch coating. The results of these studies indicate that when developing iron-fortified plant-based products, one must consider not only the level of fortification but also the retention of this element during processing, its potential bioavailability in the gastrointestinal tract, and the overall quality properties of the product.

Process time was another important factor affecting iron incorporation into beetroot tissue. Overall, extending osmotic dehydration from 30 to 120 min tended to increase iron content, although the magnitude and direction of the changes depended on the osmotic agent, iron lactate concentration, and process temperature. For example, in beetroot samples dehydrated in a 50% erythritol solution (ES50) containing 1.0% iron lactate at 40 °C, the iron content increased from 317.28 mg/100 g after 30 min to 322.44 mg/100 g after 60 min and 340.84 mg/100 g after 120 min. Four-way factorial analysis of variance confirmed a strong overall effect of process time ($F = 146.44$, $p < 0.001$, $\eta^2 = 0.803$). This tendency is consistent with our previous studies on the mineral enrichment of plant tissues with magnesium, potassium, and calcium. However, iron incorporation did not increase monotonically in every experimental combination. For example, in ES50 containing 1.0% iron lactate at 20 °C, iron content increased from 287.79 mg/100 g after 30 min to 339.05 mg/100 g after 60 min but subsequently decreased to 325.10 mg/100 g after 120 min. These results indicate that the effect of treatment duration depended on the specific combination of process variables rather than following a uniform time-dependent pattern. Comparisons with our previous studies on calcium, potassium, and magnesium suggest that the kinetics of mineral incorporation may differ depending on the mineral compound and plant matrix; however, direct mechanistic conclusions regarding mineral leaching or diffusion limitations cannot be drawn from the present data.

The effect of process temperature (20, 40, and 60 °C) on iron content was less pronounced than the effects of iron lactate concentration and process time. Temperature did not exert a significant main effect on iron content ($F = 1.22$, $p = 0.302$, $\eta^2 = 0.033$), although significant interactions involving temperature were observed. Consequently, no consistent

temperature-dependent trend was evident across all treatment combinations. In some variants, higher temperatures were associated with greater iron incorporation. For example, in beetroot samples dehydrated in a 50% inulin solution (IS50) containing 1.0% iron lactate for 120 min, the iron content increased with process temperature, from 303.59 mg/100 g at 20 °C to 316.14 mg/100 g at 40 °C and 330.07 mg/100 g at 60 °C. This finding can be considered in the context of our previous studies on the enrichment of plant tissues with magnesium, potassium, and calcium, in which increasing the process temperature promoted mineral incorporation. In the present study, however, temperature did not exert a significant main effect on iron content, indicating that its influence depended on the specific combination of process variables. Higher temperatures may reduce the viscosity of concentrated inulin and erythritol solutions and may also modify tissue permeability, potentially facilitating mass transfer. Nevertheless, these mechanisms were not directly investigated in the present study. Likewise, the absence of a uniform temperature-dependent trend suggests that the effect of temperature on iron incorporation was complex and may have reflected simultaneous changes in water loss, solute transfer, and tissue properties. The results indicate that increasing the process temperature is not always necessary to achieve a high iron content in beetroot tissue. This is confirmed by selected experimental variants, in which high levels of this element were already obtained at 20 °C. For example, in beetroot samples dehydrated in a 50% erythritol solution containing 1.0% iron lactate, an iron content of 339.05 mg/100 g was observed after 60 min at 20 °C, whereas the highest iron content in the entire experiment (340.84 mg/100 g) was recorded in samples treated with the same osmotic solution for 120 min at 40 °C.

This observation suggests that the appropriate selection of an osmotically active substance, iron salt concentration, and processing time may allow for achieving a high level of enrichment under less intense thermal conditions. A similar relationship was observed by Karlińska et al. [35], who demonstrated an increase in the content of polyphenolic compounds in apples as the concentration of plant extracts in the osmotic solution increased. Although these studies concerned different substances and a different plant matrix, both experiments highlight the importance of the concentration of the component introduced from the osmotic solution in modifying the chemical composition of plant tissues. In the case of this study, however, it is particularly important to achieve very high iron contents even at relatively low concentrations of iron lactate. This observation suggests that further optimization of the process should focus not only on maximizing enrichment but also on the ability to control the iron content in the product.

Layeghinia et al. [36] also demonstrated the effect of osmotic dehydration as a pretreatment prior to drying on the chemical composition of plant material using quince fruit as a study subject. The authors used osmotic dehydration in sucrose solutions, followed by microwave drying. Under selected process conditions, the vitamin C content increased from 8.75 to 16.33 mg/100 g dry weight, while the phenolic compound content increased from 2.95 to 3.82 mg GAE/g dry weight. However, the observed changes should not be interpreted as the direct introduction of bioactive compounds from the osmotic solution, since the sucrose used was not a source of these compounds. Changes in the content of these components may have been related to the course of subsequent processing stages, including changes in their stability. These studies indicate that osmotic dehydration, combined with an appropriately selected drying method, can influence the preservation and content of selected bioactive compounds in plant products.

The significant impact of the type of osmotic solution used on the chemical composition of the processed plant material is also confirmed by the research of Galus et al. [37]. The authors demonstrated that osmotic dehydration of orange slices in solutions prepared from fruit concentrates and rosehip juice promoted the preservation or increase in the content

of selected bioactive compounds compared to the use of conventional sucrose and xylitol solutions. For example, the highest vitamin C content was found in oranges dehydrated in rosehip juice (80.27 mg/100 g dry weight), whereas the use of sucrose and xylitol resulted in significantly lower levels (26.91 and 26.78 mg/100 g dry weight, respectively). These results can be related to the observations obtained in the present study, in which the type of osmotic agent and the iron compound used significantly affected the iron content in beetroot tissue. Particularly high iron contents were obtained in inulin and erythritol solutions, especially when iron lactate was used.

Lopez et al. also demonstrated the significant importance of the composition of the osmotic solution and the process conditions for the introduction of selected substances into plant tissues [8]. They studied the enrichment of apples with quercetin and fisetin during osmotic dehydration. The authors concluded that the type of osmotic agent used and the process temperature influenced the kinetics of mass transport, with higher temperatures promoting an increase in its rate. The present study also demonstrated a significant effect of the type of osmotic agent on the iron content in beetroot tissue. At the same time, temperature did not show a statistically significant main effect ($p = 0.302$), although significant interactions involving temperature and the other analyzed factors were observed. This indicates that the effect of temperature on iron content depended on the specific combination of process conditions and did not show a consistent trend across all experimental variants. It should be emphasized, however, that Lopez et al. evaluated mass transfer kinetics, whereas this study primarily analyzed the final iron content in plant tissue.

The importance of osmotic dehydration parameters for incorporation of nutrients into plant tissue was also demonstrated by Ismail et al. [38], who studied the osmotic dehydration of orange slices under reduced-pressure conditions using pomegranate juice concentrate, followed by hot air-assisted radiofrequency drying (HA-RFD). The authors concluded that appropriate selection of process conditions allowed for the modification of the chemical composition of the tissue, while simultaneously increasing the content of phenolic compounds and the antioxidant activity in the product. This study also demonstrated the significant impact of processing conditions on the iron content in beetroot tissue. A particularly interesting observation was the effect of osmotic dehydration time, which despite a statistically significant main effect, did not show a clear relationship across all analyzed variants. Extending the process generally resulted in higher iron content. However, in some combinations of factors, values obtained after 60 min were similar to or even higher than those obtained after 120 min. These observations indicate that the effect of osmotic dehydration time depended on the other process parameters, and extending it did not always lead to a further increase in iron content.

### *2.3. Antioxidant Activity and Proximate Composition of Dehydrated Beetroot*

To evaluate the effect of osmotic dehydration on the nutritional characteristics of beetroot, antioxidant activity was assessed using the DPPH, ABTS, and ORAC assays, together with the determination of protein, fat, and dietary fiber contents (Table 8).

Fresh, untreated beetroot exhibited the highest DPPH radical-scavenging activity, reaching 208.43 mg Trolox/100 g. Osmotic dehydration resulted in a significant ($p < 0.05$) reduction in DPPH activity in all tested variants, with values ranging from 81.12 to 96.74 mg Trolox/100 g, corresponding to decreases of approximately 53.6–61.1% relative to the fresh material. A similar trend was observed in the ABTS assay. The antioxidant activity of fresh beetroot, as determined by the ABTS assay, was 78.45 mg Trolox/100 g, whereas in osmotically dehydrated samples it was significantly lower, ranging from 22.14 to 38.66 mg Trolox/100 g, corresponding to reductions of approximately 50.7–71.8%. The greatest relative decrease was observed in the ORAC assay. The antioxidant activity of fresh beetroot,

as determined by the ORAC assay, was 1011.36 mg Trolox/100 g, whereas in osmotically dehydrated samples it ranged from 173.28 to 237.71 mg Trolox/100 g, corresponding to reductions of approximately 76.5–82.9%.

**Table 8.** Antioxidant activity and proximate composition of osmotic dehydrated beetroot.

| | Protein Content (g/100 g) | Fat Content (g/100 g) | Dietary Fiber Content (g/100 g) | DPPH (mg Trolox/100 g) | ABTS (mg Trolox/100 g) | ORAC (mg Trolox/100 g) |
|---|---|---|---|---|---|---|
| 1 | 1.26 ± 0.04 $^{a}$ | 0.05 ± 0.03 $^{a}$ | 1.63 ± 0.04 $^{a}$ | 93.80 ± 2.34 $^{a}$ | 31.07 ± 0.59 $^{a}$ | 197.21 ± 1.94 $^{a}$ |
| 2 | 1.45 ± 0.04 $^{b}$ | 0.11 ± 0.03 $^{a}$ | 1.71 ± 0.03 $^{a}$ | 81.12 ± 2.27 $^{b}$ | 22.14 ± 0.63 $^{b}$ | 173.28 ± 2.86 $^{b}$ |
| 3 | 1.32 ± 0.04 $^{ab}$ | 0.22 ± 0.05 $^{b}$ | 1.66 ± 0.03 $^{a}$ | 96.74 ± 1.32 $^{a}$ | 38.66 ± 0.58 $^{c}$ | 237.71 ± 3.51 $^{c}$ |
| 4 | 1.39 ± 0.03 $^{ab}$ | 0.29 ± 0.03 $^{b}$ | 1.71 ± 0.04 $^{a}$ | 85.32 ± 0.82 $^{b}$ | 30.82 ± 0.77 $^{a}$ | 218.03 ± 2.08 $^{d}$ |
| 5 | 1.92 ± 0.10 $^{c}$ | 0.30 ± 0.03 $^{b}$ | 2.42 ± 0.04 $^{b}$ | 208.43 ± 2.02 $^{c}$ | 78.45 ± 0.41 $^{d}$ | 1011.36 ± 14.32 $^{e}$ |

a, b, c, d, e—different letters indicate statistically significant differences ($p < 0.05$). Sample 1—beet tissue dehydrated in a 50% inulin solution, with 1.0% iron lactate added, at 40 °C for 120 min; Sample 2—beet tissue dehydrated in a 50% inulin solution, with 1.0% iron lactate added, at 60 °C for 120 min; Sample 3—beet tissue dehydrated in a 50% erythritol solution with 1.0% iron lactate added, at 40 °C for 120 min; Sample 4—beet tissue dehydrated in a 50% erythritol solution, with 1.0% iron lactate added, at 60 °C for 120 min; Sample 5—fresh beet tissue not subjected to osmotic dehydration.

Process temperature significantly affected the antioxidant activity of osmotically dehydrated beetroot. Increasing the dehydration temperature from 40 to 60 °C resulted in significantly lower antioxidant activity, as determined by the DPPH, ABTS, and ORAC assays, in beetroot samples treated with both 50% inulin and 50% erythritol solutions. The lowest values in all three assays were obtained for beetroot dehydrated in 50% inulin solution containing 1.0% iron lactate at 60 °C for 120 min: 81.12 mg Trolox/100 g for DPPH, 22.14 mg Trolox/100 g for ABTS, and 173.28 mg Trolox/100 g for ORAC. The type of osmotic agent also influenced antioxidant activity, although the effect depended on the assay used. At both temperatures, samples dehydrated in erythritol solution exhibited significantly higher ABTS and ORAC values than the corresponding samples treated with inulin. In contrast, the differences between erythritol- and inulin-treated samples were not statistically significant in the DPPH assay. The differences between the results of the DPPH, ABTS, and ORAC tests should be considered in the context of the different principles underlying these assays. The DPPH method is based on measuring the ability of antioxidants to reduce the stable DPPH• radical, whereas the ABTS method measures the ability to quench the ABTS•+ cation radical. The ORAC test, on the other hand, determines the ability of antioxidants to protect fluorescein from oxidation caused by peroxyl radicals generated during the degradation of AAPH. Unlike the DPPH and ABTS tests, the ORAC method takes into account the course of the reaction over time. Differences in the type of reaction, measurement conditions, and the reactivity of individual sample components may influence the results obtained. Since the study did not determine the content of individual antioxidant compounds before and after osmotic dehydration, it is not possible to unequivocally identify the components responsible for the observed discrepancies. The results of all three tests should therefore be considered complementary indicators of the antioxidant activity of the tested samples. The lower antioxidant activity measured by the DPPH, ABTS, and ORAC assays may reflect losses of endogenous antioxidant compounds during osmotic dehydration, including betalain pigments and phenolic compounds, through leaching into the osmotic medium and possible degradation during processing.

The decrease in antioxidant activity observed after osmotic dehydration of beetroot is consistent with the results of studies conducted on other plant materials. Chiu et al. [39], in analyzing the osmotic dehydration of *Solanum lasiocarpum* Dunal fruits in sucrose solutions, demonstrated a decrease in antioxidant activity as measured by the DPPH method,

with increasing temperature and longer processing times exacerbating these changes. The authors attributed the observed changes primarily to the migration of water-soluble antioxidant compounds from the plant tissue into the osmotic solution. This study also found a significant decrease in antioxidant activity following osmotic dehydration of beetroot. The results in the DPPH assay were lower by approximately 53.6–61.1%, in the ABTS assay by 50.7–71.8%, and in the ORAC assay by 76.5–82.9% compared to the fresh material. Furthermore, increasing the process temperature from 40 to 60 °C resulted in a significant decrease in antioxidant activity in both inulin and erythritol solutions. The consistency of these trends with the observations of Chiu et al. suggests that osmotic dehydration conditions may significantly affect the preservation of the antioxidant properties of plant material. Potential causes of the decrease in antioxidant activity include the migration of soluble antioxidants into the osmotic solution and their modification during osmotic dehydration. However, since the concentrations of these compounds in the solutions after the process were not determined in this study, the contribution of individual mechanisms cannot be clearly established.

Similar changes in antioxidant activity during osmotic dehydration were described by Wojtyś et al. [40] in studies on Japanese quince fruit, using erythritol and sucrose solutions. The authors observed a significant decrease in the content of phenolic compounds, vitamin C, and antioxidant activity as determined by the DPPH and ABTS methods. They also demonstrated that the extent of these changes depended on the type and concentration of the osmotically active substance used. In subsequent studies on the osmotic dehydration of apples in a xylitol solution, Wojtyś et al. [41] found a decrease in antioxidant activity, and the use of prolonged ultrasonic treatment prior to the process further exacerbated the observed losses. The results of this study also indicate that the type of osmotic solution used is significant for the antioxidant properties of the product. Beetroot samples dehydrated in erythritol solutions exhibited higher values in the ABTS and ORAC assays than the corresponding samples dehydrated in inulin solutions. However, in the case of the DPPH assay, the differences between these systems were not statistically significant. This indicates that the effect of the type of osmotic agent on the antioxidant activity also depended on the analytical method used. This observation highlights the need to consider several methods for assessing antioxidant activity when analyzing the qualitative changes that occur during the osmotic dehydration of plant materials.

Furthermore, in our previous study on beetroot osmotically dehydrated in 50% inulin and erythritol solutions supplemented with potassium chloride at 30 and 50 °C for 180 min, significant reductions in antioxidant activity were observed [29]. DPPH radical-scavenging activity decreased by 54.65–68.75%, ABTS activity by 41.73–66.12%, and ORAC values by 85.23–89.45% compared with fresh beetroot. The higher process temperature was also associated with lower antioxidant activity. Taken together with the present results, these findings indicate that osmotic dehydration in conventional osmotic media that are not supplemented with antioxidant-rich components may lead to substantial losses of endogenous antioxidants from plant tissue. Such losses are likely associated with bidirectional mass transfer, particularly the migration of water-soluble bioactive compounds from the tissue into the osmotic solution, and may be further intensified by thermal degradation at elevated process temperatures.

The type of osmotic solution used can significantly influence the antioxidant properties of the processed plant material. Kowalska et al. [42], in their study of the osmotic dehydration of strawberries in solutions prepared from fruit juice concentrates, demonstrated that the use of chokeberry and strawberry concentrates resulted in higher antioxidant activity values, as determined by the DPPH and ABTS methods, than in fresh material. In contrast, osmotic dehydration in a sucrose solution and in cherry juice concentrate led to a decrease

in antioxidant activity. The authors also found that the type of osmotic medium used had a significant effect on antioxidant activity, while the effect of process duration was not statistically significant.

Galus et al. [37] demonstrated a similar effect of the osmotic solution composition on the dehydration of orange slices in fruit concentrates and rosehip juice. The use of strawberry concentrate led to an increase in antioxidant activity, as determined by the ABTS method, from 7.7 mg TE/g dry weight in fresh oranges to 11.0 mg TE/g dry weight after osmotic dehydration. These results indicate that the use of solutions containing natural antioxidants may help preserve or increase the measured antioxidant activity of processed plant tissues. These results indicate that the use of solutions containing natural antioxidants may promote the preservation or enhancement of the antioxidant activity of dehydrated plant tissues.

In this study, inulin and erythritol solutions with added iron lactate were used. The aim of these treatments was primarily to facilitate osmotic dehydration and enrich the beetroot with iron, rather than to provide additional antioxidants. As a result, a decrease in antioxidant activity, as measured by the DPPH, ABTS, and ORAC methods, was observed in all analyzed variants. At the same time, samples dehydrated in erythritol solutions exhibited higher values in the ABTS and ORAC tests than the corresponding samples dehydrated in inulin solutions. A comparison of these observations with the results of Kowalska et al. [42] and Galus et al. [37] indicates that when evaluating the suitability of an osmotic solution, one should consider not only its ability to facilitate the incorporation of a selected mineral component but also the effect of the process on the antioxidant properties of the final product.

Analysis of the proximate composition showed that fresh beetroot had the highest protein (1.92 g/100 g), fat (0.30 g/100 g), and dietary fiber contents (2.42 g/100 g). Osmotic dehydration resulted in significant ($p < 0.05$) reductions in all three components compared with the fresh material. In the osmotically dehydrated samples, protein content ranged from 1.26 g/100 g in beetroot treated with 50% inulin solution containing 1.0% iron lactate at 40 °C for 120 min to 1.45 g/100 g in the corresponding inulin system processed at 60 °C. Fat content ranged from 0.05 g/100 g in the inulin-treated sample at 40 °C to 0.29 g/100 g in the erythritol-treated sample at 60 °C. Dietary fiber content varied within a relatively narrow range, from 1.63 to 1.71 g/100 g. Samples dehydrated in erythritol solutions exhibited significantly higher fat contents than the corresponding inulin-treated samples at both temperatures. In contrast, dietary fiber contents did not differ significantly among the osmotically dehydrated variants, despite small numerical differences between treatments.

### *2.4. Texture Profile Analysis (TPA)*

Texture profile analysis revealed significant differences in the mechanical properties of beetroot depending on the treatment applied (Table 9). Fresh, untreated beetroot (S2) exhibited the highest hardness, reaching 297.57 ± 19.15 N. All immersed or osmotically dehydrated samples showed significantly lower hardness than the fresh material. Immersion in water (S1) reduced hardness to 87.33 ± 4.68 N, whereas osmotic dehydration in 50% inulin (S3) and 50% erythritol (S4) solutions without iron lactate resulted in hardness values of 111.90 ± 6.65 and 77.20 ± 5.70 N, respectively.

The addition of 1.0% iron lactate was associated with higher hardness in selected treatment systems. In samples immersed in an aqueous iron lactate solution (S5), hardness reached 145.63 ± 7.80 N and was significantly higher than that of the water-treated control (S1). The greatest hardness among all treated samples was observed for beetroot dehydrated in 50% inulin solution containing 1.0% iron lactate (S6), reaching 178.40 ± 9.20 N; this value was significantly higher than that of the corresponding inulin treatment without added

iron lactate (S3). In the erythritol system, the addition of iron lactate increased hardness numerically from 77.20 ± 5.70 N in S4 to 96.70 ± 7.10 N in S7, although this difference was not statistically significant.

**Table 9.** Texture profile analysis of beetroot (TPA).

| | Hardness [N] | Adhesiveness [N × s] | Springiness [%] | Cohesiveness | Gumminess | Chewiness | Resilience |
|---|---|---|---|---|---|---|---|
| S1 | 87.33 ± 4.68 $^{ac}$ | −14.37 ± 0.75 $^{a}$ | 0.41 ± 0.02 $^{a}$ | 0.28 ± 0.02 $^{a}$ | 24.69 ± 2.63 $^{a}$ | 10.20 ± 1.58 $^{ab}$ | 0.19 ± 0.02 $^{a}$ |
| S2 | 297.57 ± 19.15 $^{b}$ | −14.10 ± 0.90 $^{a}$ | 0.52 ± 0.03 $^{cd}$ | 0.46 ± 0.03 $^{b}$ | 137.26 ± 17.74 $^{d}$ | 72.13 ± 12.78 $^{d}$ | 0.32 ± 0.03 $^{cd}$ |
| S3 | 111.90 ± 6.65 $^{c}$ | −19.23 ± 0.85 $^{bc}$ | 0.51 ± 0.02 $^{cd}$ | 0.44 ± 0.02 $^{b}$ | 49.33 ± 5.17 $^{b}$ | 25.23 ± 3.63 $^{b}$ | 0.32 ± 0.02 $^{cd}$ |
| S4 | 77.20 ± 5.70 $^{da}$ | −20.57 ± 0.85 $^{c}$ | 0.32 ± 0.02 $^{b}$ | 0.29 ± 0.02 $^{a}$ | 22.47 ± 3.20 $^{a}$ | 7.23 ± 1.48 $^{a}$ | 0.20 ± 0.02 $^{a}$ |
| S5 | 145.63 ± 7.80 $^{d}$ | −17.10 ± 0.95 $^{b}$ | 0.47 ± 0.02 $^{c}$ | 0.37 ± 0.03 $^{c}$ | 53.53 ± 6.50 $^{b}$ | 25.25 ± 4.12 $^{b}$ | 0.27 ± 0.02 $^{bc}$ |
| S6 | 178.40 ± 9.20 $^{e}$ | −19.40 ± 0.95 $^{bc}$ | 0.53 ± 0.02 $^{d}$ | 0.50 ± 0.03 $^{b}$ | 89.95 ± 9.13 $^{c}$ | 47.80 ± 6.65 $^{c}$ | 0.36 ± 0.02 $^{d}$ |
| S7 | 96.70 ± 7.10 $^{ac}$ | −19.07 ± 0.05 $^{bc}$ | 0.39 ± 0.02 $^{a}$ | 0.36 ± 0.03 $^{c}$ | 35.25 ± 5.02 $^{ab}$ | 13.82 ± 2.67 $^{ab}$ | 0.26 ± 0.02 $^{b}$ |

a, b, c, d, e—different letters indicate statistically significant differences ($p < 0.05$). S1—fresh beet placed in water; S2—fresh beet; S3—beet subjected to osmotic dehydration (50% inulin solution, without iron lactate); S4—beet subjected to osmotic dehydration (50% erythritol solution, without iron lactate); S5—beet placed in a 1.0% iron lactate solution; S6—beet subjected to osmotic dehydration (50% inulin solution, 1.0% iron lactate); S7—beet subjected to osmotic dehydration (50% erythritol solution, 1.0% iron lactate).

Cohesiveness ranged from 0.28 ± 0.02 in the water-treated sample (S1) to 0.50 ± 0.03 in S6. High cohesiveness values were also recorded for fresh beetroot (S2; 0.46 ± 0.03) and for the inulin-treated sample without iron lactate (S3; 0.44 ± 0.02), with no significant differences among S2, S3, and S6. The lowest cohesiveness values were observed in S1 and in beetroot dehydrated in erythritol without iron lactate (S4; 0.29 ± 0.02).

Springiness showed a similar treatment-dependent pattern. The highest numerical value was recorded for S6 (0.53 ± 0.02), followed closely by fresh beetroot (S2; 0.52 ± 0.03) and S3 (0.51 ± 0.02). These samples did not differ significantly from one another. The lowest springiness was observed in S4 (0.32 ± 0.02).

Fresh beetroot (S2) exhibited the highest gumminess (137.26 ± 17.74 N) and chewiness (72.13 ± 12.78 N). Among the treated samples, S6 showed the highest gumminess (89.95 ± 9.13 N) and chewiness (47.80 ± 6.65 N), whereas S4 exhibited the lowest numerical values for these parameters, at 22.47 ± 3.20 N and 7.23 ± 1.48 N, respectively.

Adhesiveness was negative in all samples and ranged from −14.10 ± 0.90 N·s in fresh beetroot (S2) to −20.57 ± 0.85 N·s in S4. The more negative adhesiveness values observed in several osmotically treated samples indicate a greater work of adhesion compared with the fresh material. Resilience ranged from 0.19 ± 0.02 in S1 to 0.36 ± 0.02 in S6. High resilience was also observed in fresh beetroot (S2; 0.32 ± 0.03) and S3 (0.32 ± 0.02), with no significant differences among S2, S3, and S6.

## 3. Materials and Methods

### *3.1. Plant Material and Sample Pre-Treatment*

Beetroot (*Beta vulgaris* L.) of the 'Czerwona Kula' cultivar was used in the study, sourced from the organic supplier "Dolina Mogilnicy" (Wolkowo, Poland). The raw material was promptly peeled and sectioned into regular cubes with dimensions of 2.0 × 2.0 × 2.0 cm. Aliquots of 50 ± 0.5 g were then weighed out, packed into dedicated vessels, and subjected to deep-freezing at −80, where they remained stored prior to the osmotic dehydration process and further experimental trials. The masses of beetroot samples measured before osmotic dehydration, after osmotic dehydration, and following freeze-drying during the first and second stage of the experiment are presented in Tables S1 and S2 (Supplementary Materials).

### *3.2. Chemicals and Reagents*

Analytical reagents, including 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), 2,2′-azobis(2-methylpropionamidine) dihydrochloride (AAPH), 2,2-diphenyl-1-picrylhydrazyl (DPPH), fluorescein, (±)-6-hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid (Trolox), potassium persulfate, anhydrous dipotassium hydrogen phosphate, sodium dihydrogen phosphate, methanol, nitric acid, and lanthanum chloride, were obtained from Sigma-Aldrich/Merck (Poznań, Poland). The osmotically active substances—specifically inulin HSI, xylitol, and erythritol—were supplied by HORTIMEX Sp. z o.o. (Konin, Poland). Iron compounds, including iron (II) lactate hydrate (catalog number: PA-03-7340-C; the compound content was 99.2% on an anhydrous basis, and the water content was 13.7%; the certificate indicated an Fe (III) content of 0.01% and concentrations of lead, cadmium, arsenic, and mercury not exceeding 0.1 ppm for each of these elements) and iron (II) gluconate dihydrate (catalog number: PA-03-4628-X) were obtained from POL-AURA (Morąg, Poland), while ammonium iron (III) citrate (catalog number: 31781) and iron (II) sulfate heptahydrate (catalog number: 61132) were obtained from WARCHEM (Zakręt, Poland). Sucrose was acquired via retail distributors. All other analytical reagents and solvents were obtained from AlfaChem (Lublin, Poland).

### *3.3. Osmotic Dehydration Procedure*

The osmotic dehydration (OD) process aimed at fortifying beetroot samples with iron was executed in two distinct experimental stages.

In the first stage, the parameters evaluated included the chemical form of iron (iron (II) lactate hydrate, iron (II) gluconate dihydrate, ammonium iron (III) citrate, and iron (II) sulfate heptahydrate), the type of osmotic agent (inulin, erythritol, xylitol, sucrose), and the osmotic solute concentration (25% and 50% *w*/*w*). Chemical forms of iron permitted for use in foods under Regulation (EC) No 1925/2006 were selected, including both organic and inorganic iron compounds differing in aqueous solubility and elemental iron content.

Osmotic solutions were prepared by dissolving either 62.5 g (for 25% *w*/*w*) or 125.0 g (for 50% *w*/*w*) of the respective osmotic agent in distilled water to obtain 250.0 g of base solution. Subsequently, the selected iron compound was introduced at a concentration of 1.0% *w*/*w* (2.5 g) under continuous stirring until fully dissolved. In the first stage of the experiment, the identical mass of each of the four iron salts (2.5 g per 250 g of the base solution) was intentionally used. The purpose of this stage was to compare the iron content in beetroot at the same mass of iron compounds used, rather than at an equivalent content of elemental iron. Due to the varying mass fractions of iron in the individual salts, the initial amount of this element in the prepared solutions therefore differed. The calculated amount of elemental iron added to hypertonic solutions upon the addition of 2.5 g of each iron compound was as follows: iron (II) gluconate—280.68 mg, iron (II) lactate—510.80 mg, ammonium iron (III) citrate—512.50 mg, and iron (II) sulfate—497.16 mg.

Samples of diced beetroots weighing 50.0 ± 0.5 g were placed in prepared osmotic solutions, maintaining a mass ratio of plant material to solution of 1:5. The sealed containers were placed in a shaking water bath (SWB 22N, Laboplay, Bytom, Poland), and the process was carried out at 50 °C for 120 min. After osmotic dehydration, the samples were drained on a laboratory sieve and weighed. The material was then frozen at −80 °C for 24 h and freeze-dried. After freeze-drying, the samples were weighed, and the material was ground in a laboratory grinder (Bosch, Munich, Germany) and prepared for iron content determination. The sample masses measured after osmotic dehydration and after freeze-drying were then used to calculate the iron content. In the second stage of the study, the effect of process parameters on iron incorporation into beetroot was evaluated using 50% solutions of inulin and erythritol selected based on the results of the first stage. This phase

investigated the multi-factorial influence of parameters: process duration (30, 60, and 120 min), temperature (20 °C, 40 °C and 60 °C), and iron compound concentration (0.5% and 1.0% *w*/*w*; corresponding to 1.25 g and 2.5 g per 250 g of solution, respectively). The prepared samples were freeze-dried and preserved following the aforementioned protocol for downstream analyses.

### *3.4. Determination of Iron Content*

Quantitative analysis of iron was performed following dry ashing. 1.0 g of the lyophilized, osmotically dehydrated sample was weighed into a quartz crucible and incinerated in a muffle furnace at 450 °C until complete mineralization was achieved. The resulting ash was quantitatively dissolved in 1 mol/L nitric acid ($HNO_3$, Suprapur, Merck). Iron concentrations were determined in triplicate using flame atomic absorption spectrometry (FAAS, Model ZA3000; Hitachi, Tokyo, Japan). This method was validated with an accuracy of 95% using a LGC7161 tomato paste with added elements, LGC Standards—certified reference material (Teddington, UK). Relative standard deviation was <5%. Based on the result obtained, expressed in mg Fe/g of freeze-dried material, and the masses of the samples determined after osmotic dehydration and after freeze-drying, the iron content was calculated on a per 100 g basis of the material after osmotic dehydration and before freeze-drying.

The percentage iron incorporation rate (%) was calculated as the ratio of the amount of iron incorporated into the beetroot during osmotic dehydration to the total amount of elemental iron added to the osmotic solution, according to the following formula:

$$IE_{Fe}(\%) = \frac{C_{OD} \cdot m_{OD} - C_0 \cdot m_0}{Fe_x}$$

$IE_{Fe}$—iron incorporation rate (%);
$C_{OD}$—iron concentration in beetroot after osmotic dehydration (mg/100 g);
$m_{OD}$—mass of beetroot after osmotic dehydration (g);
$C_0$—initial iron concentration in fresh beetroot (mg/100 g);
$m_0$—initial mass of fresh beetroot before osmotic dehydration (g);
$Fe_x$—total amount of elemental iron added to the osmotic solution (mg).

### *3.5. Extract Preparation for Antioxidant Activity Analysis*

Extraction for antioxidant potential assessment was performed based on previously established conditions [14]. Accurately weighed portions of dehydrated material (5.0 g) were transferred into conical flasks containing 50 mL of 50% aqueous methanol (MeOH:$H_2O$, 1:1 *v*/*v*). Extraction was carried out in a thermostatic shaking water bath (SWB 22N) maintained at 50 °C for 2 h. After extraction, the suspensions were subjected to centrifugation (1500 rpm, 10 min.) and gravity filtration through a filter paper. The obtained filtrates were promptly used for antioxidant assays.

### *3.6. Antioxidant Activity Analysis*

The antioxidant potential of the iron-fortified dehydrated beetroot extracts was assessed using three complementary assays: ORAC, DPPH, and ABTS.

ORAC Assay: Oxygen radical absorbance capacity was determined according to Ou et al. [43]. Extracts were diluted in 75 mM phosphate buffer (pH 7.4). The working assay mixture contained 0.04 µM sodium fluorescein and 153 mM AAPH as the peroxyl radical generator. Fluorescence decay was monitored on a spectrofluorometer (Hitachi F-2700, Tokyo, Japan) at excitation and emission wavelengths of $\lambda = 493$ nm and $\lambda = 515$ nm, respectively. Results were expressed as milligrams of Trolox equivalents per 100 g of dry matter (mg TE/100 g DM).

DPPH Radical Scavenging Assay: The scavenging activity against 2,2-diphenyl-1-picrylhydrazyl (DPPH$^{\bullet}$) was measured following Brand-Williams et al. [44]. A stock solution of DPPH (10 mL of 80% $v/v$ aqueous methanol) was prepared. For the assay, 100 µL of the sample extract was mixed with 250 µL of DPPH stock and 2.0 mL of aqueous methanol. The mixture was vortexed and incubated in the dark at room temperature (22) for 20 min. Absorbance was recorded at λ = 517 using a UV-Vis spectrophotometer (Metertech SP 830, Taipei, Taiwan). Results were expressed as milligrams of Trolox equivalents per 100 g of dry matter (mg TE/100 g DM).

ABTS Radical Cation Decolorization Assay: The ABTS$^{\bullet+}$ scavenging activity was evaluated as described by Re et al. [45]. The radical cation was generated by reacting an aqueous solution of ABTS (3.84 g/L) with potassium persulfate (0.664 g/L) at a 2:1 $v/v$ ratio, followed by dark incubation at 22 for 16 h. An aliquot of 30 µL of extract was combined with 3.0 mL of the activated ABTS reagent and thoroughly vortexed. After 6 min of reaction time, absorbance was measured at λ = 734 nm on a spectrophotometer (Metertech SP 830). The antioxidant capacity was expressed as mg TE/100 g DM.

### *3.7. Proximate Composition Analysis*

The proximate composition of the dehydrated beetroot was evaluated following official analytical protocols. The protein content was quantified using the Kjeldahl procedure on an automated distillation unit (Kjeltec 2200; Foss Tecator, Hoganas, Sweden) based on AOAC standards [46]. Fat content was assessed by solvent extraction using a Soxtec HT6 apparatus (Foss Tecator, Hoganas, Sweden) [47]. Total dietary fiber was determined through the enzymatic-gravimetric Asp method [48] employing a Fibertec analyzer (Foss Tecator, Hoganas, Sweden).

### *3.8. Texture Profile Analysis (TPA)*

The texture profile analysis (TPA) was performed using a TA.XTplus texturometer (Stable Micro Systems Ltd., Godalming, UK), equipped with a 35 mm-diameter cylindrical probe and version 7.0.6.0 of the analytical software (Stable Micro Systems). The samples were subjected to two compression cycles under the following parameters: pre-measurement speed of 10.0 mm/s, measurement speed of 5.0 mm/s, post-measurement speed of 5.0 mm/s, and a deformation of 40% of the sample's initial height. Six measurements were performed for each variant. The procedure was based on the method described by Kowalczewski et al. [49].

### *3.9. Statistical Analysis*

The experiments were conducted in three independent experimental replicates (n = 3), and the results are presented as mean values ± standard deviation (SD). One-way or factorial analysis of variance (ANOVA) was applied to evaluate treatment effects, with mean differences discriminated using Tukey's honest significant difference (HSD) post hoc test. For the second experimental stage, statistical analysis was performed using a four-factor analysis of variance (ANOVA) model. The independent factors investigated were the osmotic agent, iron concentration, processing time, and temperature, including both their main effects and interaction terms. Prior to the analysis, the fundamental assumptions of ANOVA were verified; the normality of data distribution and the homogeneity of variances were assessed using the Shapiro–Wilk and Levene's tests, respectively. For all verified datasets, the assumptions were found to be satisfied ($p > 0.05$). Statistical significance was defined at a threshold of $p < 0.05$. Data processing and computations were performed using Statistica software (version 13.1; StatSoft Inc., Krakow, Poland).

## 4. Conclusions

This study confirmed that osmotic dehydration facilitates the effective impregnation of beet tissue with iron, providing an effective method for increasing the iron content of plant matrices. The effectiveness of tissue saturation with this element depends on the combination of technological parameters, including the type and concentration of the osmotically active substance, the chemical form of the iron salt, and the duration and temperature of the process. This study demonstrated that the use of 50% solutions of erythritol or inulin in combination with a 1.0% addition of iron (II) lactate, with a dehydration time of 120 min, results in the highest accumulation of the element in fresh tissue (340.84 mg/100 g and 316.14–330.07 mg/100 g, respectively), which, after freeze-drying, yields an iron content of 777.51–804.15 mg/100 g of dry weight.

However, this process resulted in a decrease in antioxidant activity, which may be associated with losses of bioactive compounds during processing. Therefore, further research is needed to determine whether the antioxidant potential of the plant matrix can be preserved, for example, by enriching hypertonic solutions with plant extracts or concentrated fruit juices to compensate for the loss of bioactive metabolites.

The results confirm that it is possible to enrich beetroot with iron. However, a very high content of this element cannot be equated with safety for consumption. A limitation of the study is the lack of an assessment of product safety and iron bioavailability. Furthermore, the observed decrease in antioxidant activity and changes in textural properties indicate that the maximum iron content does not necessarily result in a product with the most favorable quality characteristics. Before its potential use as a food ingredient, it is necessary to determine the appropriate fortification level and serving size, taking into account total dietary iron intake. Further research should also include an assessment of iron bioavailability, including in vivo studies, as well as an analysis of sensory properties, microbiological stability, and changes that occur during storage. Only after obtaining this data will it be possible to assess the suitability of the material for use in the development of iron-fortified food products.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/molecules31224182/s1, Table S1: Mass of beetroot samples before osmotic dehydration, after osmotic dehydration, and after freeze-drying (stage 1); Table S2: Mass of beetroot samples before osmotic dehydration, after osmotic dehydration, and after freeze-drying (stage 2).

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## References


1. Ramya, V.; Jain, N.K. A Review on Osmotic Dehydration of Fruits and Vegetables: An Integrated Approach. *J. Food Process Eng.* **2017**, *40*, e12440. [CrossRef]
2. Asghari, A.; Zongo, P.A.; Osse, E.F.; Aghajanzadeh, S.; Raghavan, V.; Khalloufi, S. Review of Osmotic Dehydration: Promising Technologies for Enhancing Products' Attributes, Opportunities, and Challenges for the Food Industries. *Compr. Rev. Food Sci. Food Saf.* **2024**, *23*, e13346. [CrossRef] [PubMed]
3. Mari, A.; Parisouli, D.N.; Krokida, M. Exploring Osmotic Dehydration for Food Preservation: Methods, Modelling, and Modern Applications. *Foods* **2024**, *13*, 2783. [CrossRef] [PubMed]
4. Abrahão, F.R.; Corrêa, J.L.G. Osmotic Dehydration: More than Water Loss and Solid Gain. *Crit. Rev. Food Sci. Nutr.* **2023**, *63*, 2970–2989. [CrossRef] [PubMed]
5. Waliszewski, K.N.; Garcia, R.H.; Ramirez, M.; Garcia, M.A. Polyphenol Oxidase Activity in Banana Chips during Osmotic Dehydration. *Dry. Technol.* **2000**, *18*, 1327–1337. [CrossRef]
6. Dermesonlouoglou, E.K.; Giannakourou, M.; Taoukis, P.S. Kinetic Study of the Effect of the Osmotic Dehydration Pre, Treatment with Alternative Osmotic Solutes to the Shelf Life of Frozen Strawberry. *Food Bioprod. Process.* **2016**, *99*, 212–221. [CrossRef]
7. Haneef, N.; Hanif, N.; Hanif, T.; Raghavan, V.; Garièpy, Y.; Wang, J. Food Fortification Potential of Osmotic Dehydration and the Impact of Osmo, Combined Techniques on Bioactive Component Saturation in Fruits and Vegetables. *Braz. J. Food Technol.* **2024**, *27*, e2023028. [CrossRef]
8. Lopez, M.M.L.; Morais, R.M.S.C.; Morais, A.M.M.B. Flavonoid Enrichment of Fresh, Cut Apple through Osmotic Dehydration, Assisted Impregnation. *Br. Food J.* **2020**, *123*, 820–832. [CrossRef]
9. Martínez-Sánchez, C.E.; Solis-Ramos, A.C.; Rodríguez-Miranda, J.; Juárez-Barrientos, J.M.; Ramírez-Rivera, E.J.; Ruiz-López, I.I.; Gómez-Aldapa, C.A.; Herman-Lara, E. Evaluation of Ascorbic Acid Impregnation by Ultrasound, Assisted Osmotic Dehydration in Plantain. *J. Food Process. Preserv.* **2022**, *46*, e16839. [CrossRef]
10. Silva, K.S.; Fernandes, M.A.; Mauro, M.A. Effect of Calcium on the Osmotic Dehydration Kinetics and Quality of Pineapple. *J. Food Eng.* **2014**, *134*, 37–44. [CrossRef]
11. Rascón, M.P.; Huerta-Vera, K.; Pascual-Pineda, L.A.; Contreras-Oliva, A.; Flores-Andrade, E.; Castillo-Morales, M.; Bonilla, E.; González-Morales, I. Osmotic Dehydration Assisted Impregnation of *Lactobacillus rhamnosus* in Banana and Effect of Water Activity on the Storage Stability of Probiotic in the Freeze, Dried Product. *LWT* **2018**, *92*, 490, 496. [CrossRef]
12. Auerbach, M.; DeLoughery, T.G.; Tirnauer, J.S. Iron Deficiency in Adults: A Review. *JAMA* **2025**, *333*, 1813–1823. [CrossRef] [PubMed]
13. Cacoub, P.; Choukroun, G.; Cohen-Solal, A.; Luporsi, E.; Peyrin-Biroulet, L.; Peoc, K.; Andrieu, V.; Lasocki, S.; Puy, H.; Trochu, J.-N. Iron Deficiency Screening Is a Key Issue in Chronic Inflammatory Diseases: A Call to Action. *J. Intern. Med.* **2022**, *292*, 542–556. [CrossRef] [PubMed]
14. Rohr, M.; Brandenburg, V.; Brunner-La Rocca, H.P. How to Diagnose Iron Deficiency in Chronic Disease: A Review of Current Methods and Potential Marker for the Outcome. *Eur. J. Med. Res.* **2023**, *28*, 15. [CrossRef] [PubMed]
15. Cappellini, M.D.; Comin-Colet, J.; de Francisco, A.; Dignass, A.; Doehner, W.; Lam, C.S.; Macdougall, I.C.; Rogler, G.; Camaschella, C.; Kadir, R.; et al. Iron Deficiency across Chronic Inflammatory Conditions: International Expert Opinion on Definition, Diagnosis, and Management. *Am. J. Hematol.* **2017**, *92*, 1068–1078. [CrossRef] [PubMed]
16. Cheng, R.; Dhorajia, V.V.; Kim, J.; Kim, Y. Mitochondrial Iron Metabolism and Neurodegenerative Diseases. *Neurotoxicology* **2022**, *88*, 88–101. [CrossRef] [PubMed]
17. Levi, S.; Rovida, E. The Role of Iron in Mitochondrial Function. *Biochim. Biophys. Acta Gen. Subj.* **2009**, *1790*, 629–636. [CrossRef] [PubMed]
18. Winter, W.E.; Bazydlo, L.A.; Harris, N.S. The Molecular Biology of Human Iron Metabolism. *Lab. Med.* **2014**, *45*, 92–102. [CrossRef] [PubMed]
19. Sholzberg, M.; Hillis, C.; Crowther, M.; Selby, R. Diagnosis and Management of Iron Deficiency in Females. *CMAJ* **2025**, *197*, E680–E687. [CrossRef] [PubMed]
20. Balendran, S.; Forsyth, C. Non, Anaemic Iron Deficiency. *Aust. Prescr.* **2021**, *44*, 193–196. [CrossRef] [PubMed]
21. Berthou, C.; Iliou, J.P.; Barba, D. Iron, Neuro, Bioavailability and Depression. *EJHaem* **2021**, *3*, 263–275. [CrossRef] [PubMed]
22. Rabel, A.; Leitman, S.F.; Miller, J.L. Ask about Ice, Then Consider Iron. *J. Am. Assoc. Nurse Pract.* **2016**, *28*, 116–120. [CrossRef] [PubMed]
23. Allen, R.P.; Picchietti, D.L.; Auerbach, M.; Cho, Y.W.; Connor, J.R.; Earley, C.J.; Garcia-Borreguero, D.; Kotagal, S.; Manconi, M.; Ondo, W.; et al. Evidence, Based and Consensus Clinical Practice Guidelines for the Iron Treatment of Restless Legs Syndrome/Willis, Ekbom Disease in Adults and Children: An IRLSSG Task Force Report. *Sleep Med.* **2018**, *41*, 27–44. [CrossRef] [PubMed]

24. Dahlerup, J.F.; Eivindson, M.; Jacobsen, B.A.; Jensen, N.M.; Jørgensen, S.P.; Laursen, S.B.; Rasmussen, M.; Nathan, T. Diagnosis and Treatment of Unexplained Anemia with Iron Deficiency without Overt Bleeding. *Dan. Med. J.* **2015**, *62*, C5072. [PubMed]
25. Camaschella, C. Iron Deficiency. *Blood* **2019**, *133*, 30–39. [CrossRef] [PubMed]
26. Tolkien, Z.; Stecher, L.; Mander, A.P.; Pereira, D.I.; Powell, J.J. Ferrous Sulfate Supplementation Causes Significant Gastrointestinal Side, Effects in Adults: A Systematic Review and Meta, Analysis. *PLoS ONE* **2015**, *10*, e0117383. [CrossRef] [PubMed]
27. Kulczyński, B.; Suliburska, J.; Rybarczyk, M.; Gramza-Michałowska, A. The Effect of Osmotic Dehydration Conditions on the Calcium Content in Plant Matrice. *Food Chem.* **2021**, *343*, 128519. [CrossRef] [PubMed]
28. Kulczyński, B.; Suliburska, J.; Gramza-Michałowska, A.; Sidor, A.; Kowalczewski, P.Ł.; Brzozowska, A. The Effect of Osmotic Dehydration Conditions on the Magnesium Content in Beetroot (*Beta vulgaris* L.). *Molecules* **2025**, *30*, 3051. [CrossRef] [PubMed]
29. Kulczyński, B.; Suliburska, J.; Gramza-Michałowska, A.; Sidor, A.; Kowalczewski, P.Ł.; Brzozowska, A. The Effect of Osmotic Dehydration Conditions on the Potassium Content in Beetroot (*Beta vulgaris* L.). *Molecules* **2024**, *29*, 5509. [CrossRef] [PubMed]
30. de Escalada Pla, M.F.; Campos, C.A.; Gerschenson, L.N.; Rojas, A.M. Pumpkin (*Cucurbita moschata* Duchesne ex Poiret) Mesocarp Tissue as a Food Matrix for Supplying Iron in a Food Product. *J. Food Eng.* **2009**, *92*, 361–369. [CrossRef]
31. Genevois, C.; Flores, S.; de Escalada Pla, M. Effect of Iron and Ascorbic Acid Addition on Dry Infusion Process and Final Color of Pumpkin Tissue. *LWT Food Sci. Technol.* **2014**, *58*, 563–570. [CrossRef]
32. European Parliament; Council of the European Union. Regulation (EC) No 1925/2006 of the European Parliament and of the Council of 20 December 2006 on the Addition of Vitamins and Minerals and of Certain Other Substances to Foods. *Off. J. Eur. Union* **2006**, *L404*, 26–38.
33. National Institutes of Health, Office of Dietary Supplements. Iron—Fact Sheet for Health Professionals. Available online: https://ods.od.nih.gov/factsheets/Iron-HealthProfessional/ (accessed on 24 October 2026).
34. EFSA NDA Panel (EFSA Panel on Nutrition, Novel Foods and Food Allergens). Scientific Opinion on the Tolerable Upper Intake Level for Iron. *EFSA J.* **2024**, *22*, e8819. [CrossRef] [PubMed]
35. Karlińska, E.; Milala, J.; Kosmala, M.; Klewicki, R. Osmotic Dehydration of Apples in a Saccharose Solution Containing Fragrant Agrimony or Rosehip Extract. *Molecules* **2025**, *30*, 4708. [CrossRef] [PubMed]
36. Layeghinia, N.; Karimi, S.; Abbasi, H.; Silavi, K. Effect of Osmotic Dehydration on Qualitative and Nutritional Characteristics and Kinetics of Microwave Drying of Iranian Quince Slices. *J. Agric. Food Res.* **2025**, *20*, 101749. [CrossRef]
37. Galus, S.; Rybak, K.; Dadan, M.; Witrowa-Rajchert, D.; Nowacka, M. The Effect of the Use of Unconventional Solutions for Osmotic Dehydration on Selected Properties of Fresh, Cut Oranges. *Foods* **2025**, *14*, 468. [CrossRef] [PubMed]
38. Ismail, M.; Özbek, H.N.; Göğüş, F. Combined Vacuum Osmotic Dehydration by Pomegranate Juice Concentrate and Hot, Air Assisted Radiofrequency Drying to Produce Fortified Orange Slices. *Sci. Rep.* **2025**, *15*, 36001. [CrossRef] [PubMed]
39. Chiu, M.T.; Tham, H.J.; Lee, J.S. Optimization of Osmotic Dehydration of Terung Asam (*Solanum lasiocarpum* Dunal). *J. Food Sci. Technol.* **2017**, *54*, 3327–3337. [CrossRef] [PubMed]
40. Wojtyś, A.; Pietrzyk, S.; Bogacz, S.; Witkowicz, R. Osmotic Dehydration of Japanese Quince (*Chaenomeles japonica*) Fruits in Erythritol Solutions: Impact of Processing Conditions on the Kinetic Parameters and on Physicochemical and Antioxidant Properties of the Fruits. *Molecules* **2024**, *29*, 5524. [CrossRef] [PubMed]
41. Wojtyś, A.; Pietrzyk, S.; Grzesińska, K.; Witkowicz, R. Ultrasound, Assisted Osmotic Dehydration of Apples in Xylitol Solution: Effects on Kinetics, Physicochemical Properties and Antioxidant Activity. *Molecules* **2025**, *30*, 2304. [CrossRef] [PubMed]
42. Kowalska, H.; Trusinska, M.; Rybak, K.; Wiktor, A.; Witrowa-Rajchert, D.; Nowacka, M. Shaping the Properties of Osmo, Dehydrated Strawberries in Fruit Juice Concentrates. *Appl. Sci.* **2023**, *13*, 2728. [CrossRef]
43. Ou, B.; Hampsch-Woodill, M.; Prior, R.L. Development and Validation of an Improved Oxygen Radical Absorbance Capacity Assay Using Fluorescein as the Fluorescent Probe. *J. Agric. Food Chem.* **2001**, *49*, 4619–4626. [CrossRef] [PubMed]
44. Brand-Williams, W.; Cuvelier, M.E.; Berset, C. Use of a Free Radical Method to Evaluate Antioxidant Activity. *LWT Food Sci. Technol.* **1995**, *28*, 25–30. [CrossRef]
45. Re, R.; Pellegrini, N.; Proteggente, A.; Pannala, A.; Yang, M.; Rice-Evans, C. Antioxidant Activity Applying an Improved ABTS Radical Cation Decolorization Assay. *Free Radic. Biol. Med.* **1999**, *26*, 1231–1237. [CrossRef] [PubMed]
46. AOAC. Official Method for Protein. In *Official Methods of Analysis*; Method 920.87; Association of Official Analytical Chemists: Washington, DC, USA, 1995.
47. *PN-EN ISO 3947*; Starches, Native or Modified: Determination of Total Fat Content. International Organization for Standardization (ISO): Geneva, Switzerland, 2001.

48. Dziedzic, K.; Górecka, D.; Kucharska, M.; Przybylska, B. Influence of Technological Process during Buckwheat Groats Production on Dietary Fibre Content and Sorption of Bile Acids. *Food Res. Int.* **2012**, *47*, 279–283. [CrossRef]
49. Kowalczewski, P.Ł.; Walkowiak, K.; Masewicz, Ł.; Bartczak, O.; Lewandowicz, J.; Kubiak, P.; Baranowska, H.M. Gluten, Free Bread with Cricket Powder: Mechanical Properties and Molecular Water Dynamics in Dough and Ready Product. *Foods* **2019**, *8*, 240. [CrossRef] [PubMed]

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