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Editorial

Drying Technologies in Food Processing

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Recently, consumers are paying more attention to healthy diets and often seek products with a high number of bioactive compounds, such as fruit and vegetables [1,2]. Due to the seasonality of raw materials, some fruits and vegetables are available on the market in a fresh state only for a short period during the year. Furthermore, after harvesting, there can be a surplus of raw materials. Drying is one of the most frequently used processing methods that enable surplus to be handled [3,4]. However, the drying process is used in different processes during food production and has an impact on the quality of the final product [3,5]. Different methods of drying and pretreatments are used to obtain high-quality products. Osmotic dehydration could be applied as a pretreatment before the drying process to partially remove water from the cellular tissue via the immersion of fruit and vegetables in hypertonic aqueous solutions, reducing drying time, as well as decreasing process costs and improving the taste of the final product [1,6,7]. However, osmotic dehydration might also be used to obtain minimally processed fruit and vegetable products [8]. To accelerate mass transfer during osmotic dehydration and drying, in recent years, new techniques, such as pulsed-vacuum, high and low pressure, power ultrasound, pulsed electric fields, etc., have been used [9–11].

In this Special Issue, "Drying Technologies in Food Processing", a comprehensive overview of the application of emerging and unconventional technologies prior to and during osmotic dehydration is presented. These innovative approaches are employed to produce high-quality osmodehydrated and dried products. Additionally, this Special Issue offers valuable insights into the principles and fundamentals of nonthermal technologies and their applications in food processing. This will allow researchers and experts to gain valuable insights into the potential use of different technologies in food processing, enhancing the efficiency of osmotic dehydration and drying methods.

Osmotic dehydration (OD) is a well-established method in the food industry but its lengthy processing time necessitates improvements [6]. Generally, OD is based on immersing the food in a hypertonic solution. Typically, the osmotic solution contains substances like sugars, salts, or other solutes with higher concentrations than the food's natural dry matter content [12–15]. In recent years, more valuable alternatives to osmotic agents have been used for osmotic dehydration. For example, fruit juice concentrates such as strawberry, chokeberry, and cherry concentrates have been used in the osmotic dehydration of strawberries, as presented by Kowalska et al. [16]. The use of such solutions enables the enrichment of fruits with natural sugars and bioactive compounds and positively impacts the nutritional value of osmodehydrated fruits when compared to samples dehydrated in a sucrose solution. Generally, strawberries dehydrated in strawberry and chokeberry juice concentrates were characterized as having higher antioxidant activity as well as anthocyanins and vitamin C contents in comparison to fruits dehydrated in sucrose solution.

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Furthermore, fruit juice concentrates positively influenced the sugar profile of dehydrated strawberries, providing a more nutritionally valuable product.

Osmotic dehydration partially removes water from food items; thus, usually, further processing, such as drying, is necessary [17–19]. Then, the dried materials can be conveniently stored at room temperature [20].

Moreover, some aspects were presented concerning the waste valorisation of strained yoghurt whey [21], which is a by-product with significant nutritional value, but its utilization in the industry poses challenges. It has low pH and high biochemical oxygen demand, which has led to the diversion of strained yoghurt whey to non-food applications, preventing the valuable nutrients it contains from being used for human consumption. One promising direction for utilizing strained yoghurt whey involves its application as an osmotic agent during the osmotic dehydration of fruits and vegetables. This approach can yield high-quality semi-dried or dried products, such as pumpkin snacks, or food formulations like muesli and dairy products. The osmotic behavior of strained yoghurt whey, combined with other ingredients like galacto-oligosaccharides, trehalose, and ascorbic acid, has shown promise in this regard. Based on the study's findings, it is evident that pasteurized strained yoghurt whey can serve as an alternative osmotic solute for partially dehydrating fruits without adversely affecting the sensory characteristics of the final product—in this case—specifically pumpkin.

Further improvement of the osmotic dehydration process could be achieved through combination with sonication (US) as a pretreatment and supportive technique during the OD process, as described in the review article [8]. The authors described the mechanisms of both OD and US, their advantages and disadvantages and their effect on the properties of plant tissues. The current applications of ultrasound in the context of osmotic dehydration for fruits and vegetables are explored in the article. Additionally, a comparison was made between ultrasound-assisted osmotic dehydration and sonication treatment used before osmotic dehydration. Moreover, the synergistic effects of combining ultrasound with other innovative techniques or treatments in OD, such as using novel osmotic solutions, blanching, pulsed electric field, reduced pressure, and edible coatings, are thoroughly discussed in the review paper.

Generally, freeze-drying (lyophilization) is an effective method of preserving various materials. This process involves removing water from a frozen substance through sublimation, where ice transits directly from a solid to a gaseous state without passing through the liquid phase. Freeze drying retains the original structure, flavor, and nutritional value of the material, making it a preferred technique for creating high-quality, shelf-stable products [21,22]. Furthermore, when compared to other drying methods, freeze-dried products can be reconstituted more efficiently to their original state by simply adding water [7]. A study concerning dried kiwifruit-based snacks, showed that compared to hot-air drying, freeze drying proves to be more effective in preserving bioactive compounds. Nevertheless, both freeze-drying and hot-air drying methods were effective in producing high-quality snacks that were attractive to consumers. However, due to the high porosity of freeze-dried snacks, they required specific storage conditions to avoid exposure to air [21]. Additionally, by employing a freeze-drying method, dry soups with low water content (2–3%) were successfully obtained. However, the drying process resulted in significant color changes for all soups (tomato Soup, cream; beetroot soup; pumpkin soup, cream; cucumber Soup). For beetroot soups, the redness decreased notably from 39.64 to 21.91, with the freeze-dried beetroot soup displaying the lowest chroma value of 25.98 and the highest total color change of 36.74. Furthermore, the antioxidant activity and total polyphenolic content of the soups were reduced after drying, particularly for the cucumber and tomato soups [22].

The freeze-drying method is an effective but relatively expensive preservation method due to its high energy consumption under vacuum conditions and extended drying time [22]. Therefore, other methods have also been explored to obtain good-quality products with lower energy consumption. For example, Ramaj et al. [4] developed a drying approach that can be effectively utilized in designing, modeling, and optimizing cooling, aeration, and low-temperature drying processes for wheat bulks at an air temperature ranging from 10 to 50 °C, a relative humidity in the range of 20–60%, and an airflow velocity ranging from 0.15 to 1.00 m/s. By employing this model, researchers can enhance their understanding and optimization of wheat drying processes. However, the nutritional and structural changes that occur in wheat during the extended drying times required for low-temperature drying require further study.

Bialik et al. [23] investigated the impact of convective and vacuum drying at different temperatures on the bioactive components of kiwiberry. The researchers analyzed dried fruits from Geneva and Weiki cultivars, focusing on the total carotenoid content (TCC), total phenolic content (TPC), and antioxidant activity. The results revealed that the highest total carotenoid content, as well as antioxidant activity, was found in Geneva fruits dried using the vacuum method. The values of TCC ranged from 39.55 to 90.27 μg/g dry matter (d.m.), and the antioxidant activity, evaluated using DPPH and ABTS assays, ranged from 0.16 to 0.51 mg d.m./mL and from 0.05 to 0.24 mg d.m./mL, respectively. Additionally, the authors stated that the maintenance of phenolic content in kiwiberry fruits was better in the vacuum drying method than using convective drying. Samples dried at 50 °C using the vacuum method did not significantly differ from fresh material in terms of phenolic content. Interestingly, the shortest drying time was observed for samples dried at 70 °C, regardless of the drying method employed. However, altering the drying temperature from 80 to 50 °C did not produce the anticipated advantages in terms of preserving the bioactive components [23].

In the case of the production of *Kurut*, a flavor from Central Asia produced traditionally through the sun-drying of yoghurt, vacuum oven-drying and oven drying techniques at two different temperatures (35 and 45 °C) were used by Anli [24]. Both vacuum oven drying and oven drying techniques resulted in reduced drying time compared to traditional sun drying. The drying time was reduced from 2 months for traditional sun drying to 2 days for vacuum oven drying and to 8 days for oven drying. Particularly, vacuum-oven drying proved to be four times faster than oven drying in terms of *Kurut* production. Regarding quality attributes, vacuum oven drying demonstrated better maintenance of titratable acidity, color attributes, and lower hydroxymethyl furfural (HMF) values compared to the oven drying technique.

Abbaspour-Gilandeh et al. [25] studied the impact of convective drying at different temperatures (50, 60, and 70 °C) and infrared power levels (250, 500, and 750 W) on the drying kinetics, specific energy consumption, quality, and bioactive compound contents in terebinth fruit. They also used various pretreatment methods before the drying process, such as ultrasound, blanching, and microwave. Compared to convective drying, infrared drying proved to be more efficient in reducing both the drying time and energy consumption. Higher infrared powers and air temperatures speed up the drying process, leading to lower energy consumption, higher energy efficiency, and enhanced moisture diffusion. Furthermore, the various proposed pretreatment methods significantly reduced drying time and energy consumption while increasing energy efficiency, bioactive compound contents, and the overall quality of the dried samples. Among the different pretreatments utilized, microwave pretreatment yielded the best results in terms of drying time, specific energy consumption, and energy efficiency. On the other hand, US pretreatment proved most effective in preserving the bioactive compounds and the overall appearance of the terebinth fruit. Overall, this study demonstrates the potential benefits of infrared drying and the positive impact of pretreatment methods in improving the drying process, energy efficiency, bioactive compound contents, and the quality of dried terebinth fruit samples [25]. However, Nguyen et al. [26] stated that the infrared drying of avocado pulp at high temperatures (80 °C) or for extended periods could adversely affect the quality of the dried products. However, the use maltodextrin coating proved beneficial in mitigating changes during the infrared drying of avocado pulp. The highest quality of dried avocado pulp powder was achieved when subjected to infrared drying with 9% maltodextrin at 70 °C. These conditions resulted in exceptional retention levels of total polyphenols (95.1%), total chlorophylls (95.2%), and antioxidant activity (94.4%). Furthermore, the short drying time of 35–55 min minimized lipid oxidation, leading to the absence of peroxide compounds in all samples. Overall, the study demonstrates the importance of optimizing the infrared drying process parameters, including maltodextrin level and temperature, to produce high-quality avocado pulp powder with enhanced nutritional properties and stability.

Tomas-Egea et al. [27] studied the effect of the combination of a microwave with hot-air drying (HAD-MW) of raw potato at temperatures below spontaneous evaporation in order to analyze the mechanisms involved in water transport and to optimize the microwave power level. The following conditions were selected: an air temperature of 40 °C, an air velocity of 1.5 m/s and microwave energies of 0, 4 and 6 W/g. The authors reported that it was possible to apply infrared thermography (FTIR) to measure the surface temperature during HAD-MW drying. Furthermore, they reported that when hot air drying with microwaves is carried out below the temperature of spontaneous evaporation and the characteristic dimension of the sample is less than the microwave penetration depth, convection heating is mostly transformed into surface water evaporation, whereas microwave energy mostly causes an increase in the internal temperature due to the increase in the internal energy.

In the case of reducing drying time and improving product quality, different combinations of methods can be used [28]. For example, the pretreatment of plant tissue with ethanol together with ultrasound technology is another promising potential for application before the drying process [28]. This combination of treatments can reduce drying time and lower energy consumption, preserving the quality of the product. In the case of carrots subjected to a pretreatment with ethyl alcohol, when combined with ultrasound application for varying durations (5, 15, 60, and 180 s), did not significantly affect the drying kinetics, likely due to the increased tissue shrinkage compared to untreated dried tissue. Despite this, the ethanol-immersed air-dried carrot was characterized by strongly improved carotenoids content and rehydration ability, while the color remained unchanged, which is a very desirable effect, as usually, air-dried carrots rehydrate very badly, maintaining a hard texture after rehydration. However, regarding this pretreatment method, additional solutions for ethanol recovery or re-use are needed [29].

Another combination was used by Nguyen et al. [30] to obtain dried Bo Chinh Ginseng using the ultrasound-assisted heat pump drying method. The effects of drying air temperature, ultrasonic power, and intermittency ratio of the ultrasound generator on moisture effective diffusion coefficient, saponin content, and color change (ΔE) during the drying process were investigated. The results showed that increasing the drying temperature led to a significant reduction in drying time, from 12.5 h at 35 °C to 8.9 h at 40 °C and further to 5.8 h at 55 °C. Additionally, the ultrasonic power during drying played a crucial role, and the use of ultrasound powers of 40, 80, and 160 W reduced the drying times to 8.8., 7.8, and 7 h, respectively. The moisture diffusion coefficient increased with increased drying temperature as well as increased with the increase in ultrasonic power. ΔE increased with the increase in drying temperature, while it decreased as the ultrasonic power increased in the range of 40–120 W but increased when the power ranged from 120 W to 160 W. Regarding saponin content, it increased from 35 to 45 °C but decreased as the temperature continued to rise from 45 to 55 °C. Whereas after the use of ultrasound treatment and drying, it tended to increase gradually in the power range of 40–120 W (from 89.2 to 95.2%) but decreased when the power increased from 120 to 160 W (from 95.2 to 90.5%). The optimal drying conditions of Bo Chinh Ginseng were determined as a drying air temperature of 45.2 °C, ultrasonic power of 127.7 W, and an intermittency ratio of the ultrasound generator of 0.18. These conditions can enhance efficiency and preserve the desired properties of Bo Chinh ginseng during the drying process [29].

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References

1. Ciurzyńska, A.; Kowalska, H.; Czajkowska, K.; Lenart, A. Osmotic Dehydration in Production of Sustainable and Healthy Food. *Trends Food Sci. Technol.* **2016**, *50*, 186–192. [CrossRef]
2. Tylewicz, U.; Nowacka, M.; Rybak, K.; Drozdzal, K.; Dalla Rosa, M.; Mozzon, M. Design of Healthy Snack Based on Kiwifruit. *Molecules* **2020**, *25*, 3309. [CrossRef] [PubMed]
3. Radojčin, M.; Pavkov, I.; Bursać Kovačević, D.; Putnik, P.; Wiktor, A.; Stamenković, Z.; Kešelj, K.; Gere, A. Effect of Selected Drying Methods and Emerging Drying Intensification Technologies on the Quality of Dried Fruit: A Review. *Processes* **2021**, *9*, 132. [CrossRef]
4. Ramaj, I.; Schock, S.; Müller, J. Drying Kinetics of Wheat (*Triticum aestivum* L., cv. 'Pionier') during Thin-Layer Drying at Low Temperatures. *Appl. Sci.* **2021**, *11*, 9557. [CrossRef]
5. Witrowa-Rajchert, D.; Rzaca, M. Effect of Drying Method on the Microstructure and Physical Properties of Dried Apples. *Dry. Technol.* **2009**, *27*, 903–909. [CrossRef]
6. Yadav, A.K.; Singh, S.V. Osmotic Dehydration of Fruits and Vegetables: A Review. *J. Food Sci. Technol.* **2014**, *51*, 1654–1673. [CrossRef]
7. Chavan, U.D.; Amarowicz, R. Osmotic Dehydration Process for Preservation of Fruits and Vegetables. *J. Food Res.* **2012**, *1*, 202–209. [CrossRef]
8. Nowacka, M.; Dadan, M.; Tylewicz, U. Current Applications of Ultrasound in Fruit and Vegetables Osmotic Dehydration Processes. *Appl. Sci.* **2021**, *11*, 1269. [CrossRef]
9. Witrowa-Rajchert, D.; Wiktor, A.; Sledz, M.; Nowacka, M. Selected Emerging Technologies to Enhance the Drying Process: A Review. *Dry. Technol.* **2014**, *32*, 1386–1396. [CrossRef]
10. Goula, A.M.; Kokolaki, M.; Daftsiou, E. Use of Ultrasound for Osmotic Dehydration. The Case of Potatoes. *Food Bioprod. Process.* **2017**, *105*, 157–170. [CrossRef]
11. Osae, R.; Zhou, C.; Xu, B.; Tchabo, W.; Tahir, H.E.; Mustapha, A.T.; Ma, H. Effects of Ultrasound, Osmotic Dehydration, and Osmosonication Pretreatments on Bioactive Compounds, Chemical Characterization, Enzyme Inactivation, Color, and Antioxidant Activity of Dried Ginger Slices. *J. Food Biochem.* **2019**, *43*, e12832. [CrossRef] [PubMed]
12. Kowalska, H.; Kowalska, J.; Masiarz, E.; Maziarz, S.; Pochitskaya, I. The Use of Apple and Beetroot Juices to Osmotic Dehydration of Apples. *Postępy Tech. Przetwórstwa Spoż.* **2020**, *1*, 51–57.
13. Samborska, K.; Eliasson, L.; Marzec, A.; Kowalska, J.; Piotrowski, D.; Lenart, A.; Kowalska, H. The Effect of Adding Berry Fruit Juice Concentrates and By-Product Extract to Sugar Solution on Osmotic Dehydration and Sensory Properties of Apples. *J. Food Sci. Technol.* **2019**, *56*, 1927–1938. [CrossRef] [PubMed]
14. Kowalska, H.; Marzec, A.; Kowalska, J.; Ciurzyńska, A.; Czajkowska, K.; Cichowska, J.; Rybak, K.; Lenart, A. Osmotic Dehydration of Honeoye Strawberries in Solutions Enriched with Natural Bioactive Molecules. *LWT-Food Sci. Technol.* **2017**, *85*, 500–505. [CrossRef]
15. Konopacka, D.; Jesionkowska, K.; Mieszczakowska-Frąc, M.; Plocharski, W. The Usefulness of Natural Concentrated Fruit Juices as Osmotic Agents for Osmo-Dehydrated Dried Fruit Production. *J. Fruit Ornam. Plant Res.* **2008**, *16*, 275–284.
16. 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]
17. Beaudry, C.; Raghavan, G.S.V.; Rennie, T.J. Microwave Finish Drying of Osmotically Dehydrated Cranberries. *Dry. Technol.* **2003**, *21*, 1797–1810. [CrossRef]
18. Ramaswamy, H.S.; Nsonzi, F. Convective-Air Drying Kinetics of Osmotically Pre-Treated Blueberries. *Dry. Technol.* **2007**, *16*, 743–759. [CrossRef]
19. Nowacka, M.; Wiktor, A.; Anuszewska, A.; Dadan, M.; Rybak, K.; Witrowa-Rajchert, D. The Application of Unconventional Technologies as Pulsed Electric Field, Ultrasound and Microwave-Vacuum Drying in the Production of Dried Cranberry Snacks. *Ultrason. Sonochem.* **2019**, *56*, 1–13. [CrossRef]
20. Nowacka, M.; Mannozzi, C.; Dalla Rosa, M.; Tylewicz, U. Sustainable Approach for Development Dried Snack Based on Actinidia Deliciosa Kiwifruit. *Appl. Sci.* **2023**, *13*, 2189. [CrossRef]
21. Dermesonlouoglou, E.; Paraskevopoulou, E.; Andreou, V.; Taoukis, P. Osmotic Dehydration for the Production of Novel Pumpkin Cut Products of Enhanced Nutritional Value and Sustainability. *Appl. Sci.* **2020**, *10*, 6225. [CrossRef]
22. Jakubczyk, E.; Jaskulska, A. The Effect of Freeze-Drying on the Properties of Polish Vegetable Soups. *Appl. Sci.* **2021**, *11*, 654. [CrossRef]
23. Bialik, M.; Wiktor, A.; Rybak, K.; Witrowa-Rajchert, D.; Latocha, P.; Gondek, E. The Impact of Vacuum and Convective Drying Parameters on Kinetics, Total Phenolic Content, Carotenoid Content and Antioxidant Capacity of Kiwiberry (*Actinidia arguta*). *Appl. Sci.* **2020**, *10*, 6914. [CrossRef]
24. Anli, E.A. Impact of Vacuum Assisted Oven Drying of Kurut on Product Quality and Drying Characteristics. *Appl. Sci.* **2022**, *12*, 11228. [CrossRef]
25. Abbaspour-Gilandeh, Y.; Kaveh, M.; Fatemi, H.; Khalife, E.; Witrowa-Rajchert, D.; Nowacka, M. Effect of Pretreatments on Convective and Infrared Drying Kinetics, Energy Consumption and Quality of Terebinth. *Appl. Sci.* **2021**, *11*, 7672. [CrossRef]
26. Nguyen, T.V.L.; Nguyen, Q.D.; Nguyen, T.T.D.; Nguyen, P.B.D. Effects of Infrared Drying Conditions and Maltodextrin Addition on Some Physicochemical Characteristics of Avocado (*Persea americana*) Pulp Powder. *Appl. Sci.* **2021**, *11*, 11803. [CrossRef]

27. Tomas-Egea, J.A.; Traffano-Schiffo, M.V.; Castro-Giraldez, M.; Fito, P.J. Hot Air and Microwave Combined Drying of Potato Monitored by Infrared Thermography. *Appl. Sci.* **2021**, *11*, 1730. [CrossRef]
28. Dadan, M.; Nowacka, M.; Wiktor, A.; Sobczynska, A.; Witrowa-Rajchert, D. Ultrasound to Improve Drying Processes and Prevent Thermolabile Nutrients Degradation. In *Design and Optimization of Innovative Food Processing Techniques Assisted by Ultrasound*; Barba, F.J., Cravotto, G., Chemat, F., Lorenzo Rodriguez, J.M., Munekata, P.E.S., Eds.; Academic Press: London, UK, 2021; pp. 55–110, ISBN 978-0-12-818275-8.
29. Dadan, M.; Nowacka, M. The Assessment of the Possibility of Using Ethanol and Ultrasound to Design the Properties of Dried Carrot Tissue. *Appl. Sci.* **2021**, *11*, 689. [CrossRef]
30. Nguyen, H.; Le, Q.H.; Le, T.D.; Pham, V.K. Experimental Research to Determine the Effect of Ultrasound in Drying Bo Chinh Ginseng by Ultrasound-Assisted Heat Pump Drying Method. *Appl. Sci.* **2022**, *12*, 11525. [CrossRef]