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Research Article

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Transitions of Food Drying Processes toward Industry 5.0

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Abstract: Novel food drying technologies minimally alter essential nutrients and sensory qualities of food. Industry 4.0 technologies reduce the cost and time of production, energy, and resource consumption in food drying processes—transitions toward Industry 5.0 supported developing collaboration between human beings and machines to shift from a focus from economic value towards societal value. This study aims to deliver an updated, detailed analysis of the integration and applications of artificial intelligence, robotics, and the Internet of Things in the food-drying industry. The illustrated thermal food drying techniques in the study are infrared radiation, microwave, and heat pump drying, and the nonthermal processing techniques are pulse-electric field and ultrasound. Results indicated that when considering heat pump drying, artificial intelligence has the highest, and the Internet of Things has the least number of publications. In infrared radiation drying publications, artificial intelligence has the highest number, and robotics has the least publications. Further, microwave drying publications indicated the highest number of publications with artificial intelligence and the least with the Internet of Things. In pulse electric field applications for drying, the Internet of Things has the highest, and robotics has the least publications. In ultrasound applications on drying, artificial intelligence has the highest, and robotics has the most minor publications. In conclusion, artificial intelligence has the most applications, and the Internet of Things has the least applications in food drying processes. Further, Industry 4.0 is a tech-focused approach that provides solutions for problems related to food drying. At the same time, Industry 5.0 is a value-focused approach that considers human-centricity, resiliency, and sustainability in food drying.

Keywords: Artificial Intelligence, Food processing, Internet of Things, Robotics.

Introduction

According to the United Nations [1], the global population will reach approximately 9.7 billion by 2050. As a result, food demand is projected to increase significantly, with estimates indicating a rise of 35% to 56% from 2010 to 2050 [2]. Therefore, the food processing sector seeks improvements to enhance nutritional value, reduce resource consumption, and reduce environmental impact [3].

Drying technologies are primary unit operations in the food processing sector to reduce the moisture content and preserve food. Furthermore, drying extends the shelf life of food, inhibits microbial contamination, and prevents adverse chemical reactions, including both enzymatic and non-enzymatic browning. Additionally, drying helps preserve nutrients, including macronutrients and bioactive compounds. Since food materials typically contain moisture ranges between 75%-90%, reducing below 10% through vaporization demands significant energy (2.8 kJ/kg water). Starch and starchy products are highly energy-dense food items since their manufacturing process involves multiple stages of adding and removing water through thermal processing [4, 5].

Conventional food drying technologies often cause uneven and prolonged exposure to high temperatures and degrade the heat-sensitive nutrients and flavors. Also, uneven temperature distribution can lead to the hardening of food materials. Regarding energy efficiency, over 85% of industrial thermal dryers in the food industry exhibit an energy efficiency of only 30%, constituting 90% of the total processing costs [6]. Additionally, 35–45% of the energy input is lost as hot exhaust gases, contributing to significant energy wastage and greenhouse gas emissions [7].

The food industry is actively seeking measures to improve conventional drying methods and explore alternative drying techniques to overcome the limitations of conventional drying technologies. Innovative food drying technologies prevent the degradation of essential nutrients and sensory attributes of food. Due to the growing consumer demand for clean, safe food that maintains its nutritional and sensory qualities, this study aims to present a comprehensive review of the applications of robotics, artificial intelligence, and the Internet of Things in thermal and non-thermal food processing techniques. The study covers thermal food drying techniques, including infrared radiation, microwave and heat pump drying, and nonthermal processing techniques, such as pulse-electric field and ultrasound.

Materials And Methods

The literature search was conducted on peer-reviewed publications in English, covering the period from January 1, 2012, to December 31, 2023. Relevant studies were gathered from the Scopus electronic database. A set of search terms was employed to index the titles, keywords, and abstracts of these publications. The search terms utilized are illustrated in Figure 1.

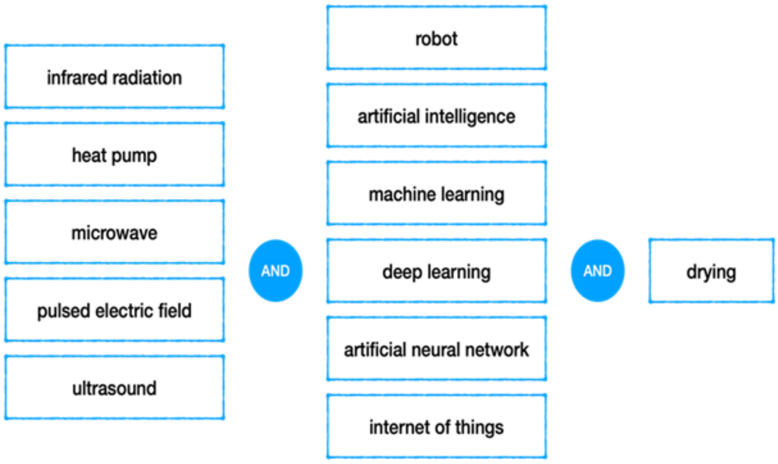

Figure 1: *Search terms for literature search queries*

The considered thermal and non-thermal processing techniques were "infrared radiation", "microwave", "heat pump" "pulsed electric field", "and ultrasound". The incorporated advanced technologies considered were "robots," "artificial intelligence," and "The Internet of Things." The term "artificial intelligence" was further refined using the specific terms "artificial neural network," "machine learning", and "deep learning". The broader term "drying" was included in all search strings to encompass all relevant literature, even though the study focused on food drying. This approach helped overcome the challenges of defining 'food materials' while searching the literature. Applying more general terms resulted in a larger set of references, which were then evaluated for relevance in subsequent stages. An example of an entry query string used in the advanced search was [TITLE-ABS-KEY ("Heat pump" AND "drying" AND "robot") AND PUBYEAR > 2012 AND PUBYEAR < 2024].

The citation information, including Author(s), Document title, Year, Source title, Volume, issues, pages, Citation count, Source & document type, Publication stage, DOI, Open access and Abstracts, and keyword information, including Abstract, Author keywords, Indexed keywords were collected through CSV files. The initial references were stored in Numbers 1.0 on macOS X and used as a database to sort them according to the selection criteria. The studies were categorized according to the drying methods, and publications and citations per year were graphed. The publications related to “artificial neural network,” “machine learning”, “deep learning”, and “artificial intelligence” were combined and considered as literature related to “artificial intelligence,” and the repetitions were removed.

Historical Overview Of The Industrial Revolution In The Food Industry

Historical industrial revolutions have progressively changed the food processing industry [8], leading to significant advancements. Figure 2 provides a detailed historical overview of the Industrial Revolution in food drying.

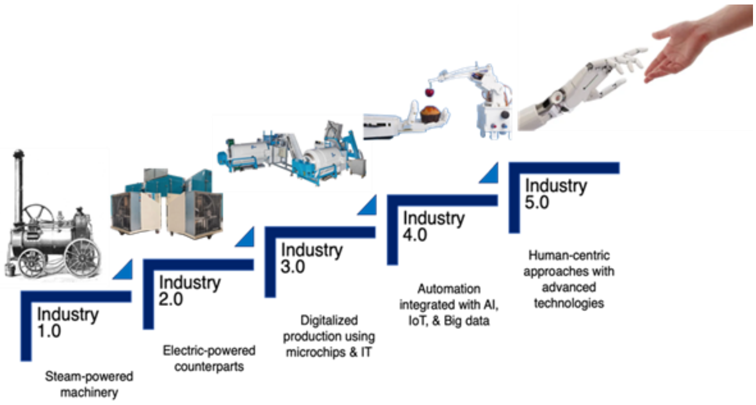

***Figure 2**: Historical overview of the Industrial Revolution in the food processing sector.*

The journal industrial revolution commenced in the late 18th century. The first industrial revolution introduced steam engines to perform repetitive tasks, leading to advancements in steam-based processes such as thermal processing. This era transitioned from reliance on human, animal, wind, or hydro-powered systems to steam-powered machinery.

Then second industrial revolution occurred in the late 19th century, replacing steam-powered machinery with electric-powered machinery. This shift further enhanced the efficiency and capabilities of industrial processes. During the 1970s, the third industrial revolution emerged, introducing the food processes digitalization through the advancement of microchips and enhanced control of food processing operations [9]. Process digitalization facilitates continuous and precise processing using programmable and automated computer features [10]. During this revolution, robotics emerged in food processing [11], and irradiation systems, including ionizing and microwave systems, were developed [12].

The transition from Industry 3.0 to 4.0 started around 2011, signifying a fundamental shift in manufacturing by digitalization and automation. Industry 3.0 introduced electronics and automation to streamline production, while Industry 4.0 integrates the Internet of Things, artificial intelligence, and big data analytics like cutting-edge technologies. This integration enables interconnectedness where machines communicate autonomously, fostering real-time monitoring and optimization. The transition promises enhanced efficiency, flexibility, and innovation in manufacturing processes in the digital era. The food processing industry is supported by the essential roles played by robotics, artificial intelligence, intelligent sensors, the Internet of Things, and big data [13, 14].

Announcing Industry 5.0 in 2021 by the European Commission supported a significant transformation in the manufacturing sector. This Industry 5.0 concept integrates human-centric approaches with cutting-edge techniques like artificial intelligence, augmented reality, and decentralized systems. Further, Industry 5.0 emphasizes the collaboration between humans and machines, integrating human creativity, intuition, and emotional intelligence into manufacturing processes. This approach seeks to harmonize human skills with advanced technologies, enhancing the industry's capacity for innovation and personalized production. Therefore, Industry 5.0 proposes a time ahead where humans and machines work consistently together, leveraging technology to augment human capabilities and foster innovation. Industry 5.0 emphasizes a more holistic approach. It integrates high technologies, focusing on improving human well-being, ensuring sustainable practices, and enhancing resilience to disruptions [15]. This approach aims to create a more balanced and sustainable industrial future by prioritizing technological progress and human values.

Overview Of Thermal Processing Techniques

Infrared Radiation Drying of Food

Infrared (IR) radiation spans around the 0.78–1,000 μm wavelength in the electromagnetic spectrum. The three regions of IR are near-infrared (0.78–1.4 μm), mid-infrared (1.4–3 μm), and far-infrared (3–1,000 μm). Although food components absorb IR radiation in all regions, most food absorbs radiation in the FIR region [16]. Water in food absorbs infrared (IR) radiation across a broad range of wavelengths, and this absorption often overlaps with that of crucial food components. This overlap complicates removing water without affecting other food components [16].

When infrared radiation strikes the surface of food, it alters the vibrational states of the atoms and molecules within it [17]. Once IR penetrates food materials, the molecules vibrate at 60,000–150,000 MHz frequency, causing friction in molecules and, thereby, causing continuous internal heating [18]. Figure 3 represents the applications of advanced technologies in infrared radiation drying.

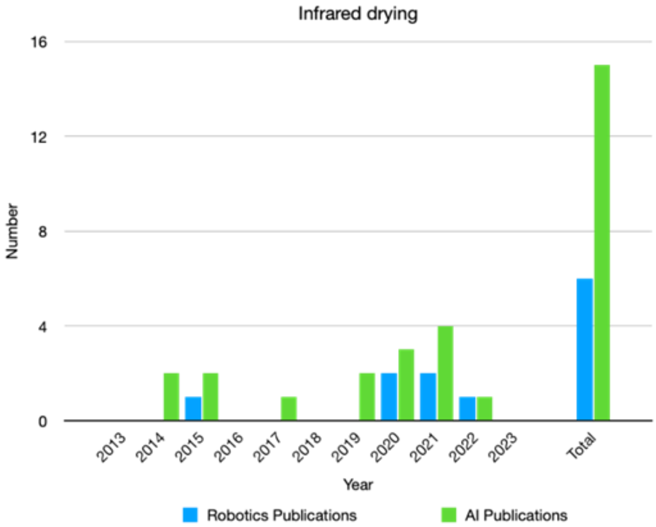

Figure 3: *Publications with the application of advanced technologies in infrared radiation drying*

Figure 3 indicates that publications with artificial intelligence applications with infrared radiation drying are higher than those with robotics. Additionally, there are no publications with Internet of Things applications in infrared radiation drying.

Microwave Drying

Microwaves are electromagnetic waves with 300 MHz and 300 GHz radio frequencies and corresponding wavelengths of 1.0 mm to 1.0 m. Once the material is exposed to the microwave field, polarization and depolarization of the charged groups of molecules occur rapidly, generating internal heat [19].

Microwave heating produces energy loss through dielectric loss when a material absorbs microwave radiation. When subjected to a high-frequency electric field, the material absorbs energy, which induces electric polarization and conduction loss in dielectric materials made of polar molecules. These polar molecules, with positive and negative poles, vibrate rapidly and intensely in response to the alternating high-frequency electric field of the microwave. Overcoming the resistance to molecular movement generates heat through friction, which raises the material's temperature [20]. Figure 4 illustrates the use of advanced technologies in microwave food drying.

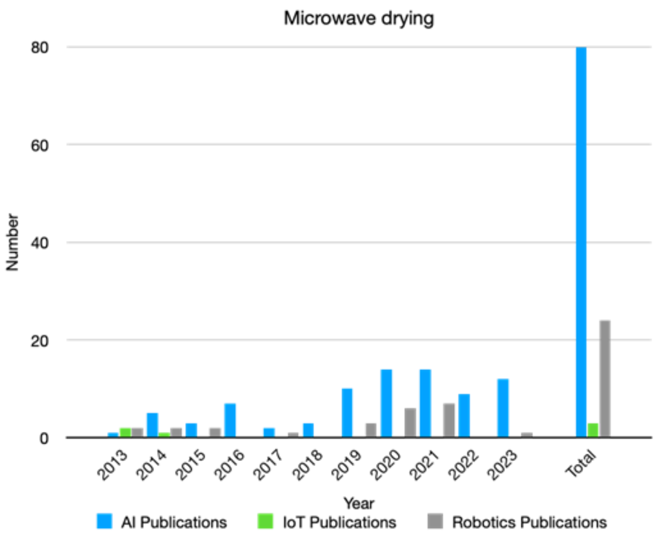

Figure 4: *Applications of advanced technologies in microwave food drying*

Figure 4 indicates that artificial intelligence has been incorporated in most publications, and the Internet of Things has the fewest in microwave food drying.

Heat Pump Drying

Heat pump drying systems combine a heat pump with a drying unit to produce humid air to remove moisture from the food materials. The refrigerant in the evaporator absorbs heat from the warm, moist air and dissipates to the dehumidified cold air at the condenser. The compressor of the heat pump unit consumes electrical energy and increases the pressure and enthalpy of the vapor refrigerant. The drying unit facilitates the drying process, providing dehumidified air to the drying unit. This technology has high energy efficiency due to the energy recovery rather than emitting waste energy to the environment. Figure 5 indicates the applications of AI, robotics, and IoT technologies in heat pump-assisted food drying.

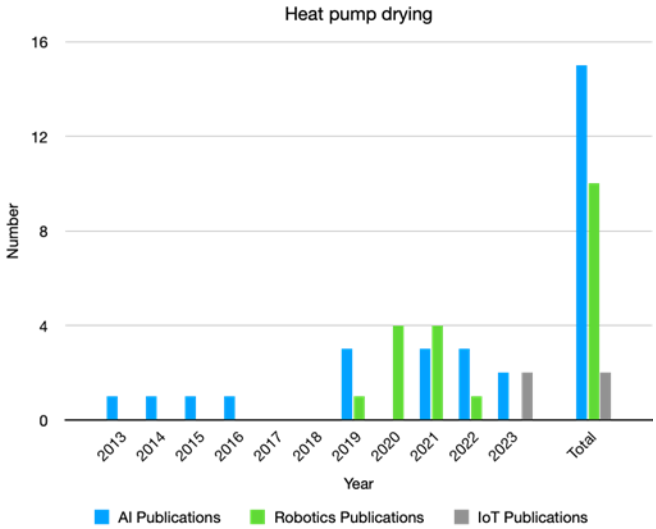

Figure 5: *Literature on AI, robotics, and IoT applications in heat pump-assisted food drying.*

Figure 5 indicates that artificial intelligence has been included in most publications, and the Internet of Things has the fewest in heat pump-assisted food drying.

Novel Non-Thermal Food Processing Techniques

Pulse-Electric Fields

Pulse-electric field-assisted drying promotes rehydration and improves the drying kinetics. High field intensity pulse at 25 to 85 kV/cm is applied to the food material for milliseconds or nanoseconds. As the food is subjected to a pulsed electric field for a limited duration, it experiences minimal heating, reducing the risk of undesirable changes associated with elevated temperatures [21, 22]. The pulse electric field device consists of a treatment chamber made of stainless steel, a control system, and a pulse generation unit. The food must be treated between two electrodes in the treatment chamber [23].

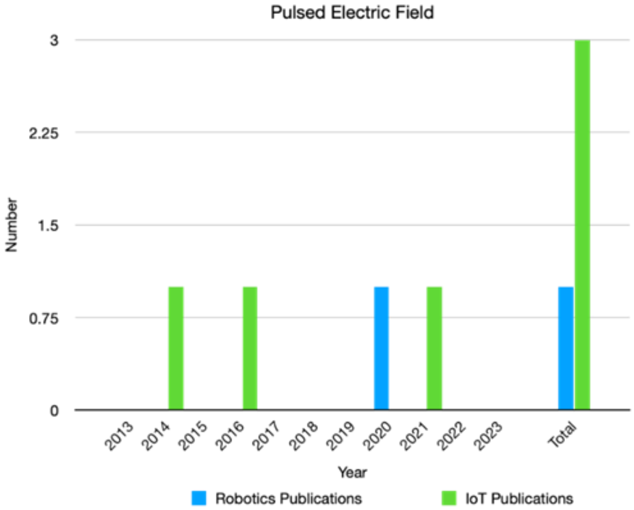

Figure 6: *Applications of advanced technologies in pulse electric field-assisted food drying.*

Figure 6 indicates that the Internet of Things has the highest number of publications, and robotics has the fewest in pulse electric field-assisted food drying. Artificial intelligence has no applications.

Ultrasound

Ultrasound is a form of sound energy transmitted through waves at frequencies of 20 kHz and above [24]. When oscillating through a medium, ultrasonic waves generate expansion and compression effects. These oscillations cause cavities within the medium to grow and collapse, generating significant energy and localized hot spots, enhancing the heat and mass transfer rates [25].

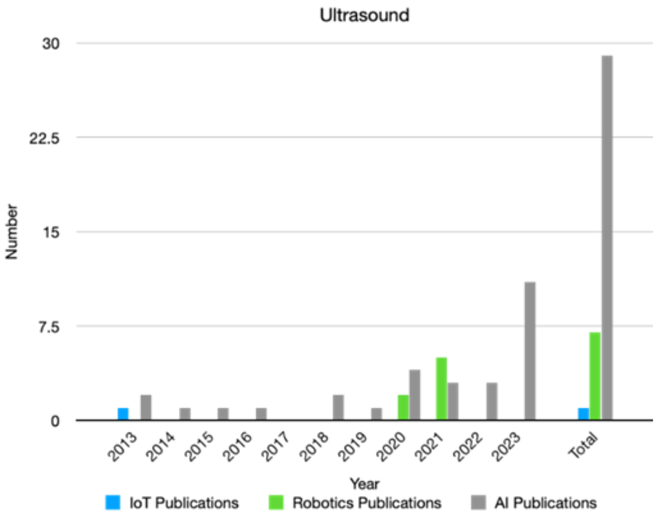

Figure 7: *Applications of advanced technologies in ultrasound-assisted food drying.*

Figure 7 indicates that artificial intelligence has the highest number of publications, and the Internet of Things has the fewest in ultrasound-assisted food drying.

Application of industry 5.0 in food processes

The European Commission's announcement of Industry 5.0 in 2021 marked a significant shift in the manufacturing sector. Industry 5.0 emphasizes the synergy between humans and machines, highlighting the importance of creativity, intuition, and emotional intelligence in manufacturing [15].

Sustainability is a fundamental principle of Industry 5.0. Drying processes, being among the most energy-intensive operations in the food industry, necessitate efforts to optimize energy consumption. This includes strategies such as improving energy efficiency, reusing energy, and integrating renewable energy sources like solar, biomass, and geothermal power.

The drying process involves the transfer of heat and moisture simultaneously. Human involvement in food drying is significant through creativity. The drying techniques can be implemented stand-alone, and several drying technologies can be combined to optimize energy consumption. Further, the final product quality and the drying process safety can be developed through human creativity and by incorporating advanced technologies. In this research study, artificial intelligence has the highest applications, and the Internet of Things has the least applications in food drying processes. Further, robotic applications are also available for drying processes.

Industry 5.0 envisions a future where humans and machines collaborate seamlessly, utilizing technology to enhance human capabilities and drive innovation. Furthermore, it is woven around humans, laying a foundation for sustainability and resilience. Integrating advanced technologies with human creativity in food drying processes offers opportunities to optimize energy use and improve product quality. Moreover, adhering to sustainability principles of Industry 5.0 entails reducing reliance on non-renewable energy sources.

Conclusion

The study concluded the status publications of Artificial Intelligence, Robotics, and the Internet of Things applied drying processes in the food industry. The thermal drying techniques considered in this study were heat pump, infrared, and microwave drying. The non-thermal processing techniques considered were ultrasound and pulsed electric field. The study concluded that Artificial intelligence has the highest applications, and the Internet of Things has the least applications in food drying processes. Additionally, Industry 4.0 offers tech-driven solutions for addressing challenges in food drying. In contrast, Industry 5.0 takes a human value-driven approach, emphasizing human-centricity, resilience, and sustainability in food drying.

References

[1]. United Nations. (2019). World population prospects 2019 - Highlights. In Department of economic and social Affairs. World population prospects 2019. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12283219.

[2]. van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nature Food, 2(7), 494–501. https://doi.org/10.1038/s43016-021-00322-9

[3]. Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockstr¨om, J. (2019). Six transformations to achieve the sustainable development goals. Nature Sustainability, 2(9), 805–814. https://doi.org/10.1038/s41893-019-0352-9

[4]. Griffin, P.W., Hammond, G.P., Norman, J.B. (2016). Industrial energy use and carbon emissions reduction: a UK perspective. Wiley Interdisciplinary Reviews: Energy and Environment, 5(6) 684-714.

[5]. Roos, Y.H., Fryer, P.J., Knorr, D., Schuchmann, H.P., Schroën, K., Schutyser, M.A.I., Trystram, G., Windhab, E.J. (2016) Food Engineering at Multiple Scales: Case Studies, Challenges and the Future—A European Perspective. Food Engineering Reviews, 8 (2), pp. 91-115.

[6]. Gremmen, B., van Haperen, P., & Lamerichs, J. (2009). In K. W. Waldron, G. K. Moates, & C. B. Fraulds (Eds.). A socio-economic perspective on co-product exploitation. Total Food- Sustainability of the Agri-Food Chain" (pp. 3–13). Cambridge, UK: The Royal Society of Chemistry.

[7]. Atuonwu, J. C., Jin, X., van Straten, G., van Deventer Antonius, H. C., & Van Boxtel, J. B. (2011). Reducing energy consumption in food drying: Opportunities in desiccant adsorption and other dehumidification strategies. Procedia Food Science, 1, 1799-1805.

[8]. Hassoun, A., Jagtap, S., Trollman, H., Garcia-Garcia, G., Abdullah, N. A., Goksen, G., ... & Lorenzo, J. M. (2023). Food processing 4.0: Current and future developments spurred by the fourth industrial revolution. Food Control, 145, 109507.

[9]. Teixeira, A. A., & Shoemaker, C. F. (1989). Introduction. In A. A. Teixeira, & C. F. Shoemaker (Eds.), Computerized food processing operations (1st ed., pp. 1–4). https://doi.org/10.1007/978-1-4615-2043-6_1

[10]. Goff, H. D., & Griffiths, M. W. (2006). Major advances in fresh milk and milk products: Fluid milk products and frozen desserts. Journal of Dairy Science, 89(4), 1163–1173. https://doi.org/10.3168/jds.S0022-0302(06)72185-3

[11]. Nayik, G. A., Muzaffar, K., & Gull, A. (2015). Robotics and food technology: A mini review. Journal of Nutrition & Food Sciences, 5(4), 1–5. https://doi.org/10.4172/2155-9600.1000384

[12]. Farkas, J., & Moh´ acsi-Farkas, C. (2011). History and future of food irradiation. Trends in Food Science & Technology, 22(2–3), 121–126. https://doi.org/10.1016/j.tifs.2010.04.002

[13]. Hassoun, A., Aït-kaddour, A., Abu-mahfouz, A. M., Rathod, N. B., Bader, F., Barba, F. J.,… Regenstein, J. (2022a). The fourth industrial revolution in the food industry — Part I: Industry 4.0 technologies. Critical Reviews in Food Science and Nutrition, 1–17. https://doi.org/10.1080/10408398.2022.2034735

[14]. Hassoun, A., Siddiqui, S. A., Smaoui, S., Ucak, ˙I., Arshad, R. N., Garcia-Oliveira, P., …Bono, G. (2022b). Seafood processing, preservation, and analytical techniques in the age of Industry 4.0. Applied Sciences, 12(3), 1703. https://doi.org/10.3390/app12031703

[15]. Breque, M., De Nul, L., & Petridis, A. (2021). Industry 5.0: towards a sustainable, human-centric and resilient European industry. Luxembourg, LU: European Commission, Directorate-General for Research and Innovation.

[16]. Delfiya, D. A., Prashob, K., Murali, S., Alfiya, P. V., Samuel, M. P., & Pandiselvam, R. (2022). Drying kinetics of food materials in infrared radiation drying: A review. Journal of Food Process Engineering, 45(6), e13810.

[17]. Sakai N, Hanzawa T (1994) Applications and advances in far-infrared heating in Japan. Trends Food Sci Technol 5:357–362

[18]. Fasina, O., Tyler, B., Pickard, M., Zheng, G. H., & Wang, N. (2001). Effect of infrared heating on the properties of legume seeds. International journal of food science & technology, 36(1), 79-90.

[19]. Rattanadecho, P., & Makul, N. (2016). Microwave-assisted drying: A review of the state-of-the-art. Drying Technology, 34(1), 1-38.

[20]. Guzik, P., Kulawik, P., Zając, M., & Migdał, W. (2022). Microwave applications in the food industry: An overview of recent developments. Critical Reviews in Food Science and Nutrition, 62(29), 7989-8008.

[21]. Niu, D., Zeng, X. A., Ren, E. F., Xu, F. Y., Li, J., Wang, M. S., & Wang, R. (2020). Review of the application of pulsed electric fields (PEF) technology for food processing in China. Food Research International, 137, 109715.

[22]. Vorobiev, E., & Lebovka, N. (2019). Pulsed electric field in green processing and preservation of food products. In Green food processing techniques (pp. 403-430). Academic Press.

[23]. Arshad, R. N., Abdul-Malek, Z., Munir, A., Buntat, Z., Ahmad, M. H., Jusoh, Y. M., ... & Aadil, R. M. (2020). Electrical systems for pulsed electric field applications in the food industry: An engineering perspective. Trends in food science & technology, 104, 1-13.

[24]. Witrowa-Rajchert, D., Wiktor, A., Sledz, M., & Nowacka, M. (2014). Selected emerging technologies to enhance the drying process: A review. Drying Technology, 32(11), 1386-1396.

[25]. Bhangu, S. K., & Ashokkumar, M. (2017). Theory of sonochemistry. Sonochemistry: From Basic Principles to Innovative Applications, 1-28.