

EMERGING NON-THERMAL APPROACHES IN POTATO PROCESSING: OPPORTUNITIES AND CHALLENGES

M. Selvamuthukumar^{*1}

ABSTRACT: Non-thermal processing techniques are emerging as innovative methods in the potato processing industry, offering opportunities to improve product quality at a commercial scale. These approaches enhance the stability of processed potatoes by reducing microbial load, preserving physico-chemical properties, and minimizing nutrient degradation during processing. Techniques such as high-pressure processing, pulsed electric fields, cold plasma, and irradiation have demonstrated potential in maintaining the sensory, nutritional, and functional attributes of potato products. While each method offers distinct advantages, limitations related to cost, equipment availability, and process optimization remain. This review highlights recent developments in non-thermal processing of potatoes, emphasizing their applications, benefits, and challenges. The integration of these technologies in potato processing can ensure improved safety, extended shelf life, and retention of nutritional quality in various potato-based products.

KEYWORDS: Non-thermal, pulsed electric field, ohmic heating, potato frying, high pressure processing

INTRODUCTION

Non-thermal processing technologies such as pulsed electric field (PEF), ohmic heating, irradiation, plasma treatment, high pressure processing (HP), and supercritical fluid extraction techniques have recently emerged as significant alternatives to traditional physical and chemical preservation methods for thermal processing of potatoes, particularly concerning their nutritive and organoleptic characteristics (Allai *et al.*, 2023).

The use of these technologies, whether individually or in conjunction with other natural additives, can greatly enhance the shelf stability of fresh-cut potatoes as well as potato-based processed products. Below, a brief description of the various non-thermal

processing techniques specifically employed for potato processing is provided.

Ultrasound

Ultrasound is a non-thermal food processing technique that effectively preserves food without inducing spoilage (Drouso *et al.*, 2024). The method relies primarily on the cavitation phenomenon, which involves the formation, oscillation, and collapse of microbubbles in liquids (Chemat *et al.*, 2011). High-frequency ultrasound waves, typically exceeding 20 kHz, are applied at intensities ranging from 10 to 1000 W/cm², while lower frequency applications are usually in the range of 18–100 kHz. The power intensity of an ultrasonic probe is defined as the output power (W) divided by the beam area (cm²).

^{*}Corresponding author; email: msm_foodscience@yahoo.co.in

¹Associate Professor, Krishna Institute of Science & Technology, Krishna Vishwa Vidyapeeth, Karad, Maharashtra, India

Enzyme inactivation occurs through the induction of cell membrane leakage, which helps reduce enzymatic browning in fresh-cut potatoes (Amaral *et al.*, 2017). Additionally, ultrasound treatment aids in maintaining wound healing and membrane integrity in fresh-cut produce (Qiao *et al.*, 2021).

Ultrasound (US), especially high-intensity power ultrasound, has garnered significant interest as a technology for process intensification in potato processing due to its ability to enhance mass transfer, disrupt cellular structures, and accelerate dehydration along with other physicochemical processes through acoustic cavitation. Previous research has shown that ultrasound-assisted osmotic dehydration (UAOD) can lead to increased moisture loss and soluble-solids transfer within potato tissues, effectively reducing the pre-treatment duration prior to subsequent drying operations (Goula *et al.*, 2017). More recent investigations have validated that ultrasound can offer valuable processing advantages in potato products. For instance, Cheng *et al.* (2023) found that ultrasound pre-treatment markedly improved the drying rate and decreased the drying time of potato slices during subsequent microwave-vacuum drying. Nonetheless, the effectiveness was highly contingent on the treatment medium; ultrasound-assisted osmotic dehydration utilizing a concentrated sucrose solution did not necessarily enhance drying performance, indicating that ultrasound's benefits cannot be viewed in isolation from the surrounding process conditions. Likewise, recent studies on ultrasound-assisted frying revealed a reduction in oil absorption and enhancements in the quality characteristics of potato chips, with an optimized dual-stage ultrasound treatment achieving a reduction in oil content by approximately 32% (Alikhani Chamgordani *et al.*, 2024). Furthermore, Yuan *et al.* (2025) recently demonstrated that ultrasonic-assisted

ethanol pre-treatment facilitated the formation of microchannels in potato slices, improved mass transfer during osmotic dehydration, and enhanced the quality of CO₂-puffed dried potato products. These results suggest that the most significant potential of ultrasound may reside in its capacity to intensify existing unit operations rather than to supplant traditional potato-processing technologies.

Despite the encouraging results observed in laboratory and pilot-scale studies, the commercial application of ultrasound-assisted potato processing has not yet been widely adopted as an independent industrial technology. The primary challenge lies in the difficulty of replicating the acoustic conditions achieved in small laboratory reactors within high-throughput continuous systems. In larger processing volumes, acoustic energy is not evenly distributed due to factors such as attenuation, reflection, interference, and variations in acoustic impedance, which can lead to inconsistencies in cavitation intensity. As a result, merely increasing the reactor size or ultrasonic power does not guarantee a corresponding rise in treatment capacity. Furthermore, the treatment response is influenced by several factors, including potato size, tissue structure, moisture content, temperature, solid-to-liquid ratio, ultrasound frequency, amplitude, and exposure duration. Recent engineering reviews have highlighted reactor design, cavitation uniformity, transducer configuration, and continuous-flow operation as significant obstacles to scaling up for industrial use (Cárcel *et al.*, 2024). Research is currently underway to explore advanced multi-transducer and large-area reactor designs to address these challenges; however, their effectiveness in continuous industrial potato-processing settings still needs to be validated.

Another significant limitation pertains to the complexity of equipment and the

required capital investment. Industrial ultrasound systems necessitate high-power generators, transducers or sonotrodes, reactors, temperature-control systems, and process-monitoring equipment. When dealing with large throughput, multiple transducers or several treatment stages may be essential to achieve adequately uniform acoustic exposure, which in turn raises capital costs and maintenance demands. Additionally, transducer degradation, fouling, and a decline in acoustic efficiency can further escalate maintenance expenses. Recent reviews have highlighted that the high cost of equipment, matrix-dependent acoustic propagation, the absence of standardized processing protocols, and challenges in ensuring uniform treatment are key factors hindering the widespread adoption of ultrasound in food processing (Tarafdar *et al.*, 2024; Gallo *et al.*, 2025). Furthermore, the lack of standardized criteria for reporting ultrasonic power, acoustic intensity, energy density, and the actual energy delivered to the food matrix complicates comparisons between studies and poses challenges for industrial process design.

A further critical limitation is the complexity of the equipment and the associated capital investment. Industrial ultrasound systems demand high-power generators, transducers or sonotrodes, reactors, temperature-control systems, and process-monitoring equipment. For large throughput, it may be necessary to employ several transducers or multiple treatment stages to achieve sufficiently uniform acoustic exposure, which increases both capital costs and maintenance requirements. Moreover, issues such as transducer degradation, fouling, and a reduction in acoustic efficiency can lead to higher maintenance costs. Recent reviews have pointed out that the high cost of equipment, matrix-dependent acoustic propagation, the lack of standardized processing protocols,

and the difficulties in maintaining uniform treatment are among the main factors that limit the large-scale implementation of ultrasound in food processing (Tarafdar *et al.*, 2024; Gallo *et al.*, 2025). The absence of standardized criteria for reporting ultrasonic power, acoustic intensity, energy density, and the actual energy delivered to the food matrix also complicates the comparison of studies and hinders the design of industrial processes.

Another notable limitation is the complexity of the equipment and the significant capital investment required. Industrial ultrasound systems require high-power generators, transducers or sonotrodes, reactors, temperature-control systems, and process-monitoring equipment. In scenarios involving large throughput, multiple transducers or several treatment stages may be necessary to ensure sufficiently uniform acoustic exposure, which in turn raises capital costs and maintenance obligations. Additionally, transducer degradation, fouling, and a decrease in acoustic efficiency can further increase maintenance costs. Recent reviews have underscored that the high cost of equipment, matrix-dependent acoustic propagation, the lack of standardized processing protocols, and the challenges in achieving uniform treatment are among the primary factors that restrict the large-scale adoption of ultrasound in food processing (Tarafdar *et al.*, 2024; Gallo *et al.*, 2025). Furthermore, the lack of standardized criteria for reporting ultrasonic power, acoustic intensity, energy density, and the actual energy delivered to the food matrix complicates the comparison between studies and poses challenges for the design of industrial processes.

The economic viability of ultrasound cannot be assessed merely by labeling the technology as energy efficient. While ultrasound has the potential to decrease processing time and possibly lower

energy usage in subsequent operations, a comprehensive economic evaluation must take into account the costs associated with equipment acquisition, installation, electricity usage, cooling, maintenance, transducer replacement, cleaning and sanitation, labor, and integration with current processing systems. Recent analyses have highlighted that the economic benefits of ultrasound are significantly dependent on the specific process, and that favorable laboratory outcomes do not necessarily lead to a positive return on investment when applied at an industrial level (Gallo *et al.*, 2025). Furthermore, high-intensity systems may demand more electrical input compared to the low-intensity laboratory systems often described as “low-energy” technologies. Consequently, future studies on potatoes should provide detailed information on specific energy consumption (kWh kg^{-1}), processing capacity (kg h^{-1} or t h^{-1}), equipment costs, operating expenses, product yield, and payback period, rather than focusing solely on treatment duration and product quality outcomes.

The relatively low economic value associated with bulk raw potatoes is a significant factor to consider. Justifying a dedicated ultrasound installation may prove challenging when the technology offers only slight enhancements in color, texture, or drying time. The economic rationale becomes more compelling for high-throughput and higher-value products, such as French fries, potato chips, dehydrated potato products, and specialty potato ingredients, where even minor improvements in yield, oil absorption, processing duration, or product quality can lead to a notable financial impact. This indicates that the commercial application should be assessed on a product-specific and line-specific basis, rather than presuming that ultrasound will be economically beneficial for all potato products.

Crucially, recent literature suggests that ultrasound should not be dismissed as a technology lacking industrial potential. High-power ultrasound has already proven commercially viable in certain food-processing applications, especially where it can be integrated into existing processes and yield measurable enhancements in throughput, separation, or product functionality. Nevertheless, potato processing introduces additional complexities due to the heterogeneous nature of potato tissue and the extremely high throughputs necessary for commodity products. Consequently, current research advocates for a more cautious perspective: ultrasound is technically promising but commercially specific in its applications, with its most immediate potential lying in its integration with established processes such as osmotic dehydration, drying, frying, or extraction, rather than serving as a complete substitute for traditional processing.

As a result, future investigations should progress from laboratory optimization to pilot and demonstration-scale techno-economic evaluations. Research should analyse both ultrasound-assisted and conventional processing on a standardized mass basis, documenting throughput, specific energy consumption, water and chemical needs, product yield, quality retention, capital expenditures, operating costs, and projected payback periods. Additionally, long-term continuous operation should be assessed to evaluate transducer stability, cleaning requirements, and treatment uniformity. This information is crucial for assessing whether the quality and process-intensification advantages noted in laboratory studies can deliver sufficient economic benefits to warrant industrial investment. Based on the current evidence, ultrasound should be regarded as a promising emerging technology for process

intensification in specific potato applications, although it has not yet achieved status as a universally accepted commercial-scale potato processing technology (Cárcel *et al.*, 2024; Tarafdarf *et al.*, 2024; Gallo *et al.*, 2025).

Pulsed electric field (PEF)

In the processing of potatoes, pulsed electric field (PEF) treatment is typically applied prior to the cutting stage, which follows peeling (Leong *et al.*, 2022; Botero-Uribe *et al.*, 2017) (Figure 1). PEF induces the formation of temporary pores in the cell membranes, leading to a reduction in turgor pressure and a partial loss of structural integrity. This contributes to enhanced tissue rigidity and firmness. The pros and cons of using PEF during processing of potatoes is given in Table 1.

PEF-induced electroporation enhances membrane permeability and leads to a decrease in intracellular water and turgor pressure, which typically results in diminished firmness and cutting resistance of fresh potato tissue. PEF-induced electroporation enhances membrane permeability and leads to a decrease in intracellular water and turgor pressure, which typically results in diminished firmness and cutting resistance of fresh potato tissue.

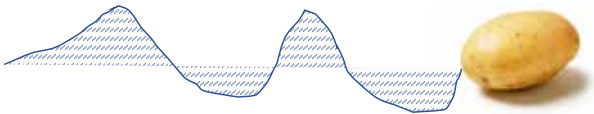


Fig.1. Application of PEF to potatoes during processing

Nevertheless, during later stages of dehydration or frying, the created porous microstructure aids in moisture movement and may help in forming a firmer and crispier outer layer following significant water loss (Lee *et al.*, 2024; Katsouli *et al.*, 2024).

The application of PEF above the electroporation threshold leads to the formation of pores in potato cell membranes, which enhances membrane permeability and results in a reduction of intracellular turgor pressure. As a result, fresh potato tissue that has undergone PEF treatment typically becomes softer and more flexible, which diminishes its resistance to mechanical forces such as cutting, thus lowering the likelihood of fracture and breakage during slicing (Golberg *et al.*, 2016; Moens *et al.*, 2021; Katsouli *et al.*, 2024). The degree of softening is influenced by factors such as electric-field strength, the number of pulses, specific energy input, and the structural properties of the potato tissue. Recent research has demonstrated that an increase in PEF intensity and pulse count can significantly decrease the firmness of fresh-

Table 1. Pros and cons of using PEF for potato processing

Pros	References	Cons	References
It can function at reduced temperatures, which helps to retain the heat-sensitive nutrients throughout the processing.	Arshad <i>et al.</i> (2020)	High capital expenditure may limit adoption; however, reduced cutting losses, improved yield, faster mass transfer and lower oil/energy use can offset investment in high-throughput potato processing.	Arshad <i>et al.</i> (2020)
The organoleptic quality characteristics of the product are being preserved.	Arshad <i>et al.</i> (2020)		Arshad <i>et al.</i> (2020)
The activities of enzymes were significantly regulated.	Poojary <i>et al.</i> (2016)		
In the processing of potatoes, particularly in the production of chips, the crispiness is preserved while minimizing oil absorption..	Leong <i>et al.</i> (2022) Zhang <i>et al.</i> (2021 & 2022).		

cut potato tissue due to ongoing disruption of cellular membranes (Katsouli *et al.*, 2024). Nevertheless, this initial softening should not be mistaken for the texture of the final fried, dried, or cooked product. During further processing, the membrane permeabilization induced by PEF aids in the migration of water and solutes and modifies the microstructure of the tissue, while the removal of moisture, transformation of starch, and formation of crust can greatly alter the final mechanical characteristics. Therefore, PEF should not be characterized as universally enhancing tissue rigidity or firmness; its immediate effect on fresh potato tissue is predominantly softening, while the ultimate texture is contingent upon the conditions of subsequent processing and the intensity of treatment (Leong *et al.*, 2022; Katsouli *et al.*, 2024).

Furthermore, exposure of potato slices to PEF promotes the development of a porous tissue structure, facilitating more efficient water removal. This modification improves the frying process and reduces oil uptake in potato products (Leong *et al.*, 2022; Zhang *et al.*, 2021, 2022).

The oil absorption of potato slices was significantly reduced to 20% following PEF treatment at 5 kV/cm, which was attributed to modifications in tissue porosity and microstructure (Zhang *et al.*, 2022). When PEF treatment was combined with drying at 60°C, the maximum cutting forces related to firmness were improved, particularly at PEF intensities of 1–1.5 kV/cm (Iaccheri *et al.*, 2022). Abduh *et al.* (2019) reported that physico-chemical properties, including thermal stability and starch gelatinization behavior, remained largely unchanged in shredded potatoes subjected to PEF treatment.

Furthermore, PEF treatment applied prior to frying markedly reduced acrylamide concentration to 10 ng/g fresh weight, with

only trace amounts detectable (Zhang *et al.*, 2021). Moreover, it has been observed that PEF treatment prior to frying significantly decreases the formation of acrylamide in potato products, suggesting a potentially advantageous food-safety aspect when suitable treatment conditions are utilized (Zhang *et al.*, 2021).

PEF treatment also has the capacity to alter starch digestibility and the textural attributes of French fries made from steam-peeled potato tubers (Leong *et al.*, 2022).

From a nutritional standpoint, a decrease in starch digestibility may be viewed as advantageous if it correlates with increased resistant starch formation or a reduced predicted glycemic response; however, excessive alterations to starch structure could affect desirable cooking and textural qualities.

Consequently, the nutritional impact of PEF should be assessed in conjunction with product texture and sensory quality, rather than being regarded as inherently beneficial or harmful.

PEF treatment can also affect the texture of the final fried product. While electroporation typically softens fresh potato tissue by disrupting cell membranes and lowering cellular turgor pressure, the end result may present a harder and crispier outer crust. This noticeable difference arises from the interplay between PEF-induced structural modifications and the frying process. Electroporation enhances membrane permeability, allowing intracellular water to migrate towards the surface. During frying, this increased water migration and evaporation hastens the dehydration of the outer layer, leading to the development of a relatively dry and mechanically robust crust. Consequently, the changes in porosity and mass transfer induced by PEF may contribute to the heightened hardness and crispness of the crust post-frying

(Leong *et al.*, 2022; Zhang *et al.*, 2022). Such an enhancement can be advantageous when it leads to improved crispness and structural integrity; however, excessive hardness may be perceived negatively from a sensory standpoint. Therefore, the impact of PEF on texture should be evaluated in the context of treatment intensity, moisture loss, frying conditions, and the desired attributes of the final product.

The economic evaluation detailed in Table 1 reveals that the primary constraint to the commercial application of PEF in potato processing is the relatively high initial capital investment required for pulse generators, treatment chambers, fluid-handling systems, control units, and their integration with existing processing lines (Arshad *et al.*, 2020). This constraint is particularly significant for potatoes, as the raw material possesses a relatively low unit value, making it challenging to accommodate a substantial additional processing cost unless the technology yields considerable enhancements in throughput, yield, or product quality. Nevertheless, the economic viability of PEF should not be assessed solely based on its capital expenditure. PEF has the potential to diminish the mechanical resistance of potato tissue, which in turn reduces cutting forces and minimizes breakage and processing losses; it can also improve mass transfer during subsequent dehydration and frying processes, potentially leading to reduced oil absorption and processing duration. These operational advantages can help mitigate the initial investment by increasing the yield of usable products, enhancing line efficiency, and decreasing downstream processing needs (Arshad *et al.*, 2020; Leong *et al.*, 2022; Katsouli *et al.*, 2024).

The economic benefits are anticipated to be more pronounced in high-throughput processing facilities that manufacture French

fries, potato chips, and other value-added items compared to smaller operations. When throughput levels are sufficiently elevated, even minor decreases in raw material losses, frying oil usage, processing duration, or energy demands can lead to substantial annual savings. Furthermore, enhanced product consistency and decreased breakage may yield indirect economic advantages through increased saleable yield and more uniform product quality. Commercial suppliers of PEF technology have reported the installation of over 100 PEF systems worldwide, including uses for potato chips and French fries; however, these figures reflect industry-reported deployments and should not be construed as independent proof of profitability for every potato processing facility. Consequently, the commercial viability of PEF should ultimately be determined through a plant-specific techno-economic analysis that takes into account capital expenditures, operating costs, throughput, specific energy consumption, yield enhancements, reductions in oil or energy usage, maintenance needs, and payback periods. For low-margin potato products, PEF is most likely to be economically feasible when incorporated into large-scale, continuous processing lines where multiple operational advantages are achieved simultaneously, rather than being applied as a standalone treatment step.

High hydrostatic pressure (HHP)

The application of high hydrostatic pressure (HHP), ranging from 100 to 1000 MPa, to foods at low temperatures for specific durations, typically between 1 and 20 minutes, has been shown to effectively inactivate or prevent enzymatic browning in fruits and vegetables. In addition, HHP inhibits microbial growth, thereby enhancing the shelf stability of treated products. A mixture

of water and ethanol, possessing suitable physico-chemical properties, was employed as a non-toxic pressure-transmitting medium to facilitate uniform pressure transmission to the potato samples. The potatoes were placed in a hyperbaric vessel (Tsikrika *et al.*, 2021), and HHP was applied in either vertical or horizontal orientations. The pros and cons of using HHP were provided in Table 2.

Polyphenol oxidase (PPO) activity was assessed following high hydrostatic pressure (HHP) processing of both peeled and unpeeled potatoes. It was observed that treatment at 600 MPa resulted in higher residual PPO activity compared to treatment at 400 MPa. Moreover, HHP treatment at 400 MPa for 6 minutes effectively suppressed microbial growth; however, it did not significantly reduce enzymatic browning in freshly cut potato sticks. This treatment was also associated with a decrease in the lightness parameter (L^*) on a scale ranging from black to white (Procaccini *et al.*, 2021).

The commercial significance of High-Pressure Processing (HPP) in the processing of potatoes goes beyond merely preserving color and inactivating enzymes. A primary application of HPP is the microbial stabilization and extension of shelf life for minimally processed, fresh-cut, refrigerated, and ready-to-eat potato products. HPP can significantly diminish microbial populations while maintaining numerous nutritional and functional properties, as the processing occurs at relatively low temperatures. In the case of minimally processed potatoes, HPP at 600 MPa has been shown to delay microbial growth during refrigerated storage and completely inhibit Enterobacteriaceae, while largely preserving total phenolic content and antioxidant activity (Tsikrika *et al.*, 2021). Additionally, HPP can affect texture by altering cellular structures, water distribution, and matrix components, which in turn influences firmness, hardness, and cohesiveness; however, these effects are highly dependent on factors such as

Table 2. Pros and cons of using high hydrostatic pressure for potato processing

Pros	References	Cons	References
It has the ability to eliminate microbes while maintaining the quality of food, without sacrificing organoleptic acceptability or nutritional value.	Argyri <i>et al.</i> (2018)	The installation requires additional investment.	Balasubramaniam <i>et al.</i> (2015)
This technique preserves the freshness, color, and texture, particularly for fresh, ready-to-eat, or minimally processed potato products.	Nguyen <i>et al.</i> (2010)	This method demands a significant amount of energy and requires substantial power for its functioning.	Balasubramaniam <i>et al.</i> (2015)
Improves microbial safety and refrigerated shelf life of minimally processed and ready-to-eat potato products; may also enable packaged-product processing, preserve bioactive compounds, modify texture and starch functionality, and reduce reliance on chemical preservatives.	Tsikrika <i>et al.</i> (2021); Gokul Nath <i>et al.</i> (2023); Colussi <i>et al.</i> (2020); Balasubramaniam <i>et al.</i> (2015)	Not all products were appropriate for their intended application due to post-treatment effects such as alterations in color, texture, and so forth. The packed material must possess a high resistance capacity when subjected to high-pressure treatment. High capital investment for pressure vessels, pumps, intensifiers, packaging and process integration can restrict economic feasibility, particularly for low-value bulk potatoes.	Gokul Nath <i>et al.</i> (2023) Marangoni Júnior <i>et al.</i> (2019) Balasubramaniam <i>et al.</i> (2015)

pressure level, treatment duration, cultivar, moisture content, and subsequent processing conditions (Gokul Nath *et al.*, 2023). Moreover, the pressure-induced alterations in starch structure and functionality can impact gelatinization, pasting behavior, and starch digestibility, thus providing opportunities for the development of potato products with modified nutritional profiles (Colussi *et al.*, 2020). HPP has also been studied for its impact on bioactive compounds, with research indicating retention of total phenolics and antioxidant activity, alterations in individual phenolic compounds, and reductions in the glycoalkaloids α -chaconine and α -solanine (Tsikrika *et al.*, 2021).

From a commercial standpoint, HPP presents several additional benefits, such as decreased reliance on chemical preservatives, enhanced microbial safety, prolonged refrigerated shelf life, and the capability to process packaged products, which helps to reduce post-process contamination (Balasubramaniam *et al.*, 2015; Tsikrika *et al.*, 2021). These advantages are especially pertinent for high-end fresh-cut and ready-to-eat potato items, rather than for low-value bulk potatoes. However, the commercial application of HPP necessitates significant investment in high-pressure vessels, pumps, intensifiers, process controls, water handling systems, and pressure-resistant packaging. Additionally, the costs associated with high-pressure cycles and equipment maintenance can add to operational expenses (Balasubramaniam *et al.*, 2015; Marangoni Júnior *et al.*, 2019). Consequently, HPP is unlikely to be economically viable for low-margin potato products that are only aimed at color or enzyme control. Its commercial viability is more pronounced in scenarios where microbial safety, extended shelf life, premium quality, packaged processing, and functional or nutritional enhancements offer

enough added value to justify the capital and operational expenditures. Therefore, future techno-economic evaluations should take into account throughput, energy usage, cost per kilogram, packaging needs, shelf-life extension, yield enhancement, and product price premiums when assessing the feasibility of HPP for potato processing.

Ohmic heating

Electrical current is conducted through foods that contain polar compounds, which aid in the flow of electricity. Fresh-cut potatoes, due to their relatively high-water content and ionic components, demonstrate adequate electrical conductivity for ohmic processing (Mari *et al.*, 2024). This conductivity facilitates the movement of ions in the aqueous phase, while the electrical resistance within the food transforms electrical energy into heat, leading to rapid and relatively uniform volumetric heating (Zareifard *et al.*, 2003). The effectiveness of ohmic heating is significantly determined by the product's electrical conductivity, which is influenced by the concentration of ionic compounds such as acids, bases, and salts (Alkanan *et al.*, 2021). Conversely, non-polar components like oils and fats have minimal impact on electrical conductivity. The primary benefits and drawbacks of ohmic heating in potato processing are illustrated in Figure 2.

Consequently, the commercial viability of ohmic heating is expected to be more significant for continuous, high-throughput, and value-added potato applications compared to low-margin bulk processing. A comprehensive economic evaluation should take into account capital investment, operational and electricity expenses, throughput, energy usage per kilogram of product, electrode longevity, maintenance needs, product yield, and possible reductions in processing time and water consumption.

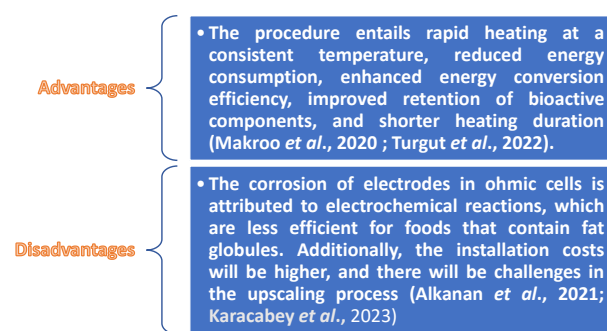


Fig.2. Advantages and disadvantages of using ohmic heating during potato processing

Currently, there is a scarcity of potato-specific techno-economic data at the industrial scale, and improvements observed in laboratory settings regarding nutrient retention or extraction efficiency alone cannot confirm commercial feasibility. Therefore, pilot and industrial-scale research that combines process performance, energy efficiency, product quality, equipment dependability, and cost per unit of processed potato is essential to assess the practical applicability of ohmic heating in large-scale potato processing.

Osmotic dehydration

Osmotic dehydration involves immersing solid food in a concentrated hypertonic solution, leading to water loss from the food and the concurrent transfer of osmo-active solutes into the tissue (Goula *et al.*, 2017; Ahmed *et al.*, 2016; Rózek *et al.*, 2010). The extent of solute diffusion into the product is influenced by several critical factors, including immersion time, nature of the food tissue, temperature, solution concentration, and agitation (González-Pérez *et al.*, 2021). The concentration of the osmotic solution is particularly crucial, as sub-critical concentrations can result in water absorption rather than dehydration (Goula *et al.*, 2017).

In the realm of commercial food processing, osmotic dehydration (OD) is

primarily utilized as a partial dehydration or pre-treatment phase, rather than serving as a complete substitute for drying. Its applications are documented in the processing of fruits and vegetables, the production of snacks and convenience foods, ingredient manufacturing, and in products that undergo subsequent air drying, frying, freezing, or other preservation methods. For potatoes, OD is especially pertinent to fresh-cut and minimally processed items and can be incorporated prior to drying or frying to decrease moisture content, alter water activity, and affect mass transfer during later processing stages. However, publicly accessible data typically does not specify the annual processing capacity directly linked to OD, as industrial facilities usually integrate OD with other unit operations and report total product throughput instead of OD-specific capacity. Consequently, the commercial viability should be assessed based on throughput, osmotic solution consumption and recovery, residence time, water removal per unit of solution, labor, energy consumption, and the requirements for downstream drying or frying, rather than presuming a distinct OD industry capacity. The primary commercial benefit of OD lies in its ability to remove water without a phase change, thus minimizing the latent heat demand associated with evaporation. Recent studies suggest that OD can eliminate roughly 30–40% of water, subsequently decreasing the load, energy needs, and residence time of air, vacuum, or other drying systems (Asghari *et al.*, 2024). Therefore, this technology is most economically viable as a hybrid pre-treatment in high-throughput processing lines rather than as an independent dehydration technique.

In comparison to traditional solar drying, osmotic dehydration (OD) offers significantly enhanced process control, as dehydration

takes place under regulated conditions of solution concentration, temperature, agitation, and processing duration. In contrast, solar drying is heavily influenced by weather variability and is more prone to issues such as contamination, extended drying times, and degradation of quality.

When compared to hot-air drying, OD functions at relatively lower temperatures and extracts moisture without necessitating its vaporization. This characteristic leads to a decrease in thermal energy requirements and minimizes heat-related damage to color, flavor, texture, and sensitive nutrients (Asghari *et al.*, 2024; Ramya and Jain, 2017). Furthermore, OD can alleviate the moisture burden on subsequent hot-air drying processes, which may result in reduced drying times and increased dryer capacity, all while lowering energy usage.

However, it is important to note that OD typically does not achieve adequate moisture reduction for complete stability at ambient temperatures, thus necessitating an additional drying or preservation phase. Challenges such as prolonged processing durations, solute absorption, management and regeneration of osmotic solutions, microbial control of the solution, and wastewater production continue to pose significant obstacles to widespread adoption (Asghari *et al.*, 2024). Therefore, the commercial benefits of OD over traditional drying methods should not be viewed merely as a replacement for existing dryers; rather, its primary advantage lies in mitigating the intensity and costs associated with subsequent drying processes while enhancing product quality. Consequently, the industrial application for potatoes should be underpinned by a techno-economic evaluation that considers capital investment, solution recycling, energy consumption, throughput, labor, savings from downstream drying,

product yield, and the market value related to quality.

In commercial practice, osmotic dehydration is widely used to reduce the water content of potatoes, thereby inhibiting microbial growth and prolonging shelf life, especially for fresh-cut potatoes destined for further processing such as drying or frying. Moreover, the spent osmotic solution can be repurposed for applications in beverage production (Ahmed *et al.*, 2016). The various osmotic agents employed in potato processing is shown in Figure 3.

Freeze drying

Freeze-drying presents promising applications in the processing of potatoes, where the preservation of quality, rehydration efficiency, and bioactive compounds offers sufficient added value to warrant its relatively high processing costs. In contrast to traditional hot-air drying, this method removes water through sublimation under vacuum, which can mitigate thermal and oxidative degradation while creating a porous

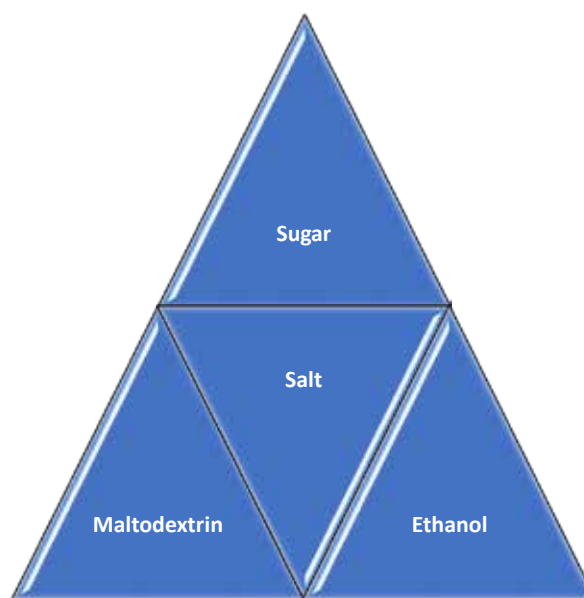


Fig.3. Various osmotic agents used in potato processing

structure that enhances rapid rehydration. This is especially beneficial for high-value potato products, including instant potato flakes or granules, dehydrated specialty potatoes, functional potato ingredients, and items designed for long-term storage. Research has indicated superior retention of heat-sensitive nutrients, polyphenols, color, structural integrity, and rehydration properties when compared to harsher thermal drying methods (Larder *et al.*, 2018; Busler *et al.*, 2017). Nevertheless, these quality benefits must be weighed against the significant drawbacks of freeze-drying, such as the substantial capital investment required for vacuum chambers and refrigeration systems, extended processing durations, high electricity usage, and the necessity for controlled freezing and vacuum conditions. As a result, freeze-drying is typically more economically viable for premium, nutrient-sensitive, or specialty potato products rather than for low-value bulk potatoes, for which hot-air or other continuous drying techniques may offer lower processing expenses. Therefore, industrial implementation should be assessed based on specific energy consumption, drying duration, throughput, product yield, equipment utilization, and enhancement of product value, rather than solely on nutritional retention. Hybrid methods, such as osmotic or convective pre-treatment followed by freeze-drying, could further decrease drying load and energy demands, thereby improving the economic viability of the process.

Irradiation

Food products can be subjected to irradiation using low-wavelength ultraviolet (UV) light, which is effective in disinfecting air, water, packaging materials, and solid surfaces (Teoh *et al.*, 2016). Exposure to UV radiation at a wavelength of 254 nm can

damage the nucleic acids of microorganisms, thereby reducing microbial contamination (Teoh *et al.*, 2016). The primary advantage of irradiation lies in its ability to replace chemical treatments, improving overall product quality, particularly in terms of food safety. As a non-thermal processing method, UV irradiation minimizes nutrient degradation in potatoes (Xie *et al.*, 2017). In commercial practice, irradiation has been employed to reduce microbial load on the surface of fresh-cut potato slices, thereby extending their shelf life. However, a limitation of UV-C irradiation is its shallow penetration depth, which primarily affects surface layers and may be less effective for dense or irregularly shaped products (Pandiselvam *et al.*, 2022). Teoh *et al.* (2016) reported that immersing potato slices in calcium chloride and ascorbic acid, followed by UV-C exposure at 6.84 kJ/m², was the most effective treatment for reducing enzymatic activities, including POD, PAL, and PPO. Moreover, the total phenolic content in treated slices remained higher during storage compared to untreated samples or those exposed to UV-C alone. The study concluded that combining chemical treatment with UV-C irradiation can enhance the shelf life of fresh-cut potatoes by inhibiting enzymatic activities.

Irradiation holds significant promise in the processing of potatoes, particularly for microbial decontamination, sprout suppression, and extending shelf life. However, its effectiveness is highly contingent upon the type of radiation used and the specific product targeted. For fresh-cut potatoes, UV-C irradiation serves as an effective surface treatment, as it can diminish microbial contamination without significantly raising the product's temperature, thereby potentially reducing reliance on chemical sanitizers (Teoh *et al.*, 2016; Pandiselvam *et*

al., 2022). Nonetheless, the limited penetration of UV-C limits its efficacy in bulk or irregularly shaped potatoes, necessitating careful consideration of uniform exposure, slice thickness, surface geometry, and dose control for practical application. Combination treatments, such as UV-C paired with calcium chloride or ascorbic acid, may offer enhanced control over enzymatic browning and quality degradation compared to UV-C used in isolation (Teoh *et al.*, 2016). Therefore, UV-C is best suited for continuously conveyed fresh-cut potato surfaces, sanitation of packaging or equipment, and other scenarios where direct exposure can be guaranteed, rather than serving as a universal solution for whole potatoes.

From an economic and industrial standpoint, UV-C systems present an appealing option due to their relatively brief treatment durations, minimal chemical requirements, and compatibility with continuous processing lines.

However, the commercial viability of these systems hinges on factors such as lamp replacement and maintenance, energy consumption, safety measures for workers, the cleanliness of lamp surfaces, and the necessity to ensure sufficient irradiation of all product surfaces. In the case of potatoes, the financial benefits may be most pronounced when UV-C technology can decrease the need for sanitizers, reduce microbial spoilage, and minimize product losses, all while prolonging refrigerated shelf life.

Conversely, traditional chemical sanitation methods may prove to be more cost-effective in situations where achieving complete surface coverage is challenging or when processing volumes are limited. Thus, the optimal implementation of UV-C technology in industrial settings must take into account various factors, including UV-C

dosage, exposure distance, conveyor speed, product loading, surface properties, microbial reduction, quality preservation, energy usage, and treatment costs per kilogram.

It is crucial to view UV-C as a specialized surface decontamination method rather than a substitute for all conventional preservation techniques. Further pilot and commercial-scale research that incorporates aspects such as microbial safety, product quality, energy consumption, equipment costs, throughput, and shelf-life extension is essential to determine its economic feasibility for large-scale potato processing.

Plasma treatment

Plasma technology can be effectively utilized as a novel method for the targeted inactivation of microorganisms. Plasma is a state of ionized gas characterized by the presence of electric fields, ultraviolet photons, charged particles, and reactive nitrogen and oxygen species (Wu *et al.*, 2022). Plasma is generated when electrical energy is applied across two electrodes with a high potential difference, leading to gas ionization as free electrons collide with gas molecules (Laroque *et al.*, 2022).

Various methods have been employed to generate plasma in food processing, including plasma jet (PJ), corona discharge (CD), dielectric barrier discharge (DBD), microwave (MW), and radiofrequency (RF) systems (Laroque *et al.*, 2022; Sakudo *et al.*, 2020). The primary antimicrobial agents responsible for plasma-induced inactivation are reactive oxygen species (ROS) and reactive nitrogen species (RNS), which can damage microbial DNA, proteins, and cell membranes (Wu *et al.*, 2022; Li *et al.*, 2019; Misra *et al.*, 2014).

The key advantages of plasma treatment include lower operational costs, reduced treatment times, and minimal energy

requirements (Sarangapani *et al.*, 2018). In large-scale commercial applications, plasma treatment can be used for surface sterilization of fresh-cut potatoes, effectively preventing enzymatic browning and microbial contamination. An indirect form of plasma treatment, known as plasma-processed air (PPA), involves remote exposure of the sample to plasma generated by a discharge device. This approach has been shown to reduce enzymatic activity, particularly polyphenol oxidase (PPO) and peroxidase (POD), by 77% and 89%, respectively, within 10 minutes of treatment (Busler *et al.*, 2017).

The use of plasma treatment in the commercial sector for potatoes is still in its early stages, and there is a lack of publicly available evidence to pinpoint significant potato-processing companies that utilize cold plasma with specified annual production capacities. This differentiation is crucial, as most documented applications are confined to laboratory or pilot scales, rather than reflecting established industrial potato-processing practices (Rajan *et al.*, 2023). Nonetheless, plasma technology presents various potential applications pertinent to the potato sector, such as the surface decontamination of fresh-cut potatoes, the reduction of enzymatic browning, the prolongation of refrigerated shelf life, the sanitation of food-contact surfaces, and pre-treatment prior to drying. Furthermore, plasma-activated water may serve as an alternative treatment medium for fresh-cut potatoes; recent studies have shown enhanced antimicrobial and anti-browning effects, as well as an extension of the shelf life of fresh-cut potatoes when organic-acid-enhanced plasma-activated water was utilized (2026). Additionally, cold filamentary microplasma has been specifically explored as a pre-treatment method for potato drying, where optimized treatment improved the drying rate and decreased the

drying duration to approximately 130 minutes without significant alterations in starch and sugar levels (2020).

From an industrial standpoint, plasma treatment presents a compelling option for continuous fresh-cut potato production lines, as it necessitates minimal or no process water or chemical sanitizers and can be seamlessly integrated with conveyors or enclosed treatment chambers. A recently designed continuous industrial-scale cold-plasma system for fresh produce utilizes modular plasma units, showcasing the feasibility of engineering systems that are suitable for integration and scaling up (2024). Nevertheless, the commercial economics specific to potatoes are not yet sufficiently established. The capital investment required for plasma generators, treatment chambers, gas supply or air-handling systems, controls, shielding, and maintenance must be weighed against potential savings in water usage, chemical sanitizers, drying time, product losses, and energy consumption. Additionally, treatment uniformity is a critical factor, as the effectiveness of plasma treatment is influenced by exposure geometry, treatment duration, gas composition, moisture levels, microbial load, and product characteristics. Consequently, instead of asserting that specific potato companies have established commercial applications, plasma should be regarded as a promising emerging technology, with its industrial viability needing validation through pilot-scale potato trials, continuous throughput studies, regulatory evaluations, and techno-economic analyses.

Supercritical CO₂ extraction

The potato peel, a by-product of the potato processing industry, remains largely underutilized despite being rich in phenolic compounds. Traditionally, organic solvents have been employed to extract these

bioactive compounds; however, a major limitation of such methods is the potential presence of residual chemicals, which may compromise food safety. Recently, novel extraction techniques have been developed that eliminate the use of harmful solvents, thereby producing phenolic extracts free from chemical residues and enhancing their applicability in food systems.

De Andrade Lima *et al.* (2021) employed the central composite design of experiments to optimize the extraction of phenolic compounds from potato peels. Their study successfully identified key phenolics, including chlorogenic acid (CGA) and caffeic acid (CFA), achieving a significant antioxidant activity of 73%. The authors reported that the optimal extraction conditions comprised 20% methanol, a temperature of 80°C, a pressure of 350 bar, and a flow rate of 18 g/min. These findings highlight the potential of potato peel as a valuable source of natural antioxidants and underscore the efficacy of advanced, solvent-free extraction methods.

CONCLUSIONS

Non-thermal and innovative processing technologies present significant opportunities to enhance the quality, safety, nutritional content, and shelf life of potato products, while also mitigating some of the drawbacks associated with traditional thermal processing. The studies reviewed suggest that pulsed electric field (PEF) technology can enhance tissue permeability, mass transfer, cutting efficiency, and subsequent frying characteristics; high-pressure processing (HPP) can achieve microbial stabilization and extend shelf life while preserving essential nutritional and bioactive components; and osmotic dehydration can lower moisture levels and the energy demands of subsequent drying processes. Freeze-drying excels in

retaining heat-sensitive compounds and improving rehydration properties, while UV-C and plasma treatments show potential for surface decontamination, controlling enzymatic browning, and preserving fresh-cut potatoes. Together, these findings illustrate that the primary advantage of emerging technologies lies not only in preservation but also in enhancing process efficiency and facilitating the creation of higher-value potato products.

Nevertheless, the evidence reviewed indicates that performance observed at the laboratory scale does not automatically equate to commercial viability. Significant barriers persist for various technologies, including high capital investment, energy demands, consistency in processes, equipment upkeep, packaging needs, limited penetration of treatments, and a lack of validation at the industrial scale. Consequently, future investigations should prioritize pilot and commercial-scale experiments, standardized processing parameters, techno-economic and life-cycle evaluations, energy efficiency improvements, and the incorporation of complementary technologies into continuous potato-processing systems. Special emphasis should be placed on the cost per kilogram of product, throughput rates, specific energy usage, enhancements in yield, prolongation of shelf life, and consumer acceptance. The field is likely to progress most effectively through interdisciplinary research that merges processing efficiency with economic and environmental assessments, facilitating the selection of technology based on product type and processing goals. Therefore, instead of pinpointing a single universally superior non-thermal technology, the evidence advocates for a product-specific and process-integrated strategy to achieve economically viable and sustainable potato processing.

CONFLICT OF INTERESTS

The author declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by the author

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