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Instant controlled pressure drop technology: A novel approach to sustainable food drying

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Abstract
Instant Controlled Pressure Drop (DIC), derived from the French term *Détente Instantanée Contrôlée*, is a rapid thermo-mechanical process in which saturated steam is followed by an abrupt pressure release into a vacuum. This sudden pressure change allows part of the internal water to flash into vapour, which can expand the internal structure and facilitate subsequent moisture removal. Because the product is heated for a relatively short period and then cooled rapidly during decompression, DIC has attracted attention as an alternative to prolonged thermal drying treatments. Research has examined DIC for swell drying, extraction, microbial decontamination, reduction of selected antinutritional compounds, and recovery of valuable components from food materials and by products. This review examines the development and operating principle of DIC, the main process variables, equipment requirements, and its effects on drying behaviour, structure, quality, and resource use. Examples involving yam chips, soybean oil extraction, and other food matrices are considered to demonstrate how DIC can be adapted to different processing objectives. The review also considers practical limitations, including equipment cost, process control, and scale up, and identifies areas where DIC could be integrated with other drying and extraction technologies.

Keywords: Instant controlled pressure drop, DIC, thermo-mechanical processing, swell drying, food drying, extraction, food preservation, bioactive compounds

Introduction

Interest in alternative drying methods has increased because achieving effective moisture removal while retaining product quality remains a major challenge. Reaching the desired final moisture content is not the only consideration in drying; the conditions used during processing can strongly influence the characteristics of the final product. Excessive or prolonged drying may result in shrinkage, cracking, colour changes, loss of volatile compounds and undesirable textural properties. For this reason, recent research has increasingly focused not only on drying kinetics but also on the structural changes that occur within the material during drying (Hamoud-Agha and Allaf, 2019 [9]; Pech-Almeida *et al*., 2021 [17]).

In plant-based foods, water removal is associated with continuous changes in the cellular structure. At the beginning of drying, moisture may move comparatively easily through the material, but continued moisture loss can cause shrinkage and structural collapse, making subsequent water movement more difficult. Instant Controlled Pressure Drop (DIC), derived from the French term Détente Instantanée Contrôlée, provides a different approach by using a rapid pressure reduction to promote the formation and expansion of internal vapour. When the pressure is suddenly reduced, part of the internal water undergoes rapid vaporization, which can create pores and expand the cellular structure. These structural changes may facilitate moisture movement during the later stages of drying (Hamoud-Agha and Allaf, 2019 [9]; Louka *et al*., 2004 [15]).

The structural characteristics produced during drying are particularly important for products that are subsequently rehydrated. Materials that undergo severe shrinkage or structural collapse may absorb water slowly and may not regain their original characteristics after rehydration. In contrast, the presence of a more open and porous structure can provide pathways for faster water penetration. Therefore, the effectiveness of DIC should not be considered only in terms of reducing drying time; its ability to influence the structure and subsequent behaviour of the dried product is also important (Pech-Almeida *et al*., 2021 [17]; Li *et al*., 2020 [13]).

Food drying has traditionally been used to improve stability and extend the storage life of perishable materials and continues to play an important role in food processing. Removing water reduces its availability for microbial growth and several deterioration reactions, thereby contributing to improved shelf stability. However, increasing the temperature or extending the drying period does not necessarily result in better processing efficiency. Prolonged exposure to elevated temperatures may adversely affect colour, flavour, texture, vitamins and other heat sensitive constituents. Conventional hot air and vacuum drying may also promote shrinkage and collapse of cellular structures, resulting in dense products with reduced rehydration capacity (Hamoud-Agha and Allaf, 2019 [9]; Chemat *et al*., 2017 [5]).

These limitations have encouraged the development of drying techniques that can improve heat and mass transfer while limiting unnecessary thermal exposure. Instant Controlled Pressure Drop (DIC) is one such technology. In this process, the material is exposed to saturated steam for a controlled period and is subsequently subjected to a sudden pressure drop into a vacuum. The rapid decompression promotes the flash evaporation of part of the internal water, generating vapour pressure within the material. This phenomenon can expand the internal pores, improve pathways for moisture movement and modify the physical structure of the product.

The potential of DIC is not restricted to improving drying performance. The structural modifications produced during pressure drop treatment can also increase the accessibility of plant tissues and influence rehydration, texture and the release of compounds present within the cellular matrix. Consequently, DIC has been explored for applications such as drying and texturing, extraction of essential oils and phenolic compounds, oilseed processing, microbial reduction and the utilization of food by products (Pech-Almeida *et al*., 2021 [17]).

An important characteristic of DIC is the combination of short duration heating with rapid cooling caused by pressure induced evaporation. Unlike conventional processes that may maintain food materials at elevated temperatures for extended periods, DIC aims to achieve the desired thermal and structural effects within a relatively short processing period. This combination has increased interest in DIC for food products where efficient moisture removal needs to be accompanied by good retention of quality characteristics (Hamoud-Agha and Allaf, 2019 [9]; Allaf and Allaf, 2014 [1]).

Historical Development of DIC Technology

DIC developed from earlier technologies used for food expansion and puffing. Early puffing methods were designed mainly to increase the volume and crispness of cereal products, while later systems incorporated steam treatment followed by rapid decompression to create expanded structures. These developments demonstrated that a sudden pressure change could not only assist moisture removal but also alter the physical structure of food materials (Allaf and Allaf, 2014 [1]; Kaur *et al*., 2023 [11]).

During the late twentieth century, continuous explosion puffing and related pressure release processes were explored to improve processing capacity and product expansion. Further research during the early 1990s contributed to the development of controlled sudden decompression systems. These advances formed the basis of modern DIC processing, where pressure, treatment duration and decompression conditions can be adjusted according to the raw material and desired product characteristics (Allaf and Allaf, 2014 [1]; Pech-Almeida *et al*., 2021 [17]).

With improvements in reactor design, vacuum generation and process control, DIC gradually progressed from an experimental technique to a potential food processing technology. Its development has been driven largely by the need to reduce processing time while maintaining desirable product qualities. Today, DIC is being explored for drying, texturization, extraction and decontamination, reflecting the expansion of the original puffing concept into a versatile processing technology (Pech-Almeida *et al*., 2021 [17]; Allaf and Allaf, 2014 [1]).

Principle of DIC Technology

The defining feature of DIC is the pressure drop event that separates DIC from ordinary steam treatment. During conventional steaming, the material is brought to the desired temperature and then remains under approximately the same pressure while heat is transferred. In DIC, the pressure is deliberately changed by opening the connection to the vacuum vessel. The resulting pressure difference is large enough to drive rapid evaporation within the material. (Hamoud-Agha and Allaf, 2019 [9]; Louka *et al*., 2004 [15])

From the standpoint of heat transfer, steam provides an efficient way of supplying energy because condensation transfers latent heat directly to the product surface. Once the pressure is suddenly reduced, part of this energy is used in the evaporation of water. This creates a useful self cooling effect. The sequence of heating followed by rapid evaporative cooling is thus important when DIC is applied to foods in which prolonged heating would be undesirable. (Hamoud-Agha and Allaf, 2019 [9]; Allaf and Allaf, 2014 [1])

Vacuum vessel design is equally important. It must be able to accept the large quantity of vapour generated during decompression without causing an uncontrolled pressure response. Similarly, the valve and connecting lines must permit the pressure to fall rapidly and reproducibly. These engineering requirements mean that DIC performance depends on the entire system, rather than on the reactor alone. (Allaf and Allaf, 2014 [1]; Hamoud-Agha and Allaf, 2019 [9])

Appropriate instrumentation is needed to determine whether a treatment is being reproduced accurately. Pressure sensors can record the treatment pressure and the decompression profile, while temperature measurements can be used to follow the thermal history of the product or the chamber. For research scale work, these measurements are particularly useful because small differences in treatment conditions can lead to visible differences in expansion and drying behaviour. (Hamoud-Agha and Allaf, 2019 [9]; Pech-Almeida *et al*., 2021 [17])

The DIC cycle can be viewed as a controlled sequence of vacuum creation, steam treatment, pressure release and evacuation. The food material is first placed in a sealed pressure resistant chamber. Depending on the system and product, an initial vacuum may be created to remove air and facilitate contact between the material and steam. Saturated steam is then admitted, rapidly increasing the temperature and pressure around the material (Hamoud-Agha and Allaf, 2019 [9]).

The product is held at the selected steam condition only long enough to achieve the intended thermal and structural effect. The defining step follows: a large valve or equivalent pressure release device connects the processing chamber rapidly to a vacuum vessel. The pressure can fall from the treatment condition to a few kilopascals in a very short time. Water inside the product responds to the pressure change by undergoing rapid evaporation. The associated vapour expansion pushes against the surrounding matrix and can open pores or enlarge existing pathways. (Hamoud-Agha and Allaf, 2019 [9]; Louka *et al*., 2004 [15])

This mechanism helps explain the influence of DIC on both drying and texture. Once the structure becomes more open, the resistance to later moisture movement may decrease. At the same time, the rapid evaporation removes heat from the material, so the product cools quickly after decompression. This combination of structural opening and rapid cooling is one of the principal reasons DIC is considered useful for heat sensitive materials. (Pech-Almeida *et al*., 2021 [17]; Louka *et al*., 2004 [15])

A typical DIC system comprises a pressure rated reactor, a steam generation and delivery system, a vacuum vessel or tank, vacuum pumping equipment, pressure control and isolation valves, and instrumentation for monitoring pressure and temperature. The pressure release valve is particularly relevant because the speed of decompression determines the intensity of the expansion effect. Modern systems may also include automated controls for treatment

pressure, residence time, vacuum level and cycle repetition. (Allaf and Allaf, 2014 [1]; Hamoud-Agha and Allaf, 2019 [9])

Factors Affecting DIC Processing

Raw material geometry must also be considered during optimization. Small cubes, thin slices and powders do not respond to steam and pressure changes in the same way as large pieces. In a thick sample, the centre may require more time to reach the desired condition, whereas a thin sample may respond almost immediately. A treatment developed for one size thus cannot automatically be transferred to another without validation. (Louka *et al*., 2004 [15]; Pech-Almeida *et al*., 2021 [17])

Material composition also affects the response. Foods containing starch, protein, fibre, sugar and different amounts of structural polysaccharides have different mechanical strengths and water binding properties. During rapid decompression, a rigid matrix may resist expansion, while a weaker or more elastic matrix may expand readily. The same pressure drop condition can thus produce very different pore structures in different foods. (Pech-Almeida *et al*., 2021 [17]; Allaf and Allaf, 2014 [1])

Pre-treatment can further modify DIC behaviour. Osmotic treatment, freezing, blanching, soaking and partial drying have all been considered in combinations with pressure-based processing. Such steps can alter moisture distribution or weaken the cellular matrix before decompression. The selection of a pre-treatment should nevertheless be based on the intended quality attributes, because an additional processing step can also increase time and energy demand. (Li *et al*., 2019 [12]; Li *et al*., 2020 [13])

Steam pressure is among the first variables to evaluate when designing a DIC treatment. Increasing pressure generally raises the treatment temperature and increases the amount of energy available for rapid evaporation. However, a higher setting is not automatically better. Excessive pressure or an unsuitable holding time may damage fragile tissues, alter colour or accelerate undesirable reactions. The appropriate condition thus depends on the product, its moisture content and the desired degree of expansion. (Louka *et al*., 2004 [15]; Hamoud-Agha and Allaf, 2019 [9])

Treatment time is closely linked with pressure. DIC is intended to provide a high temperature treatment over a short period, so unnecessarily long exposure may reduce some of the quality advantages of the process. The best treatment is the shortest one that provides adequate heating and structural modification. Product size and geometry also matter because heat and moisture must move through the material before the pressure drop occurs. (Hamoud-Agha and Allaf, 2019 [9]; Louka *et al*., 2004 [15])

Initial moisture content is especially relevant because the expansion effect depends on the presence of water that can vaporize rapidly. A material that is too dry may not develop sufficient internal vapour pressure for strong expansion, whereas excessive moisture may increase the energy requirement and affect the final texture. Moisture equilibration before treatment has thus been investigated as a way of making expansion more uniform, especially in products such as apple cubes. (Li *et al*., 2020 [13]; Pech-Almeida *et al*., 2021 [17])

The number of DIC cycles can also influence the resulting structure. Repeating the pressure drop step may further open the matrix and increase accessibility during extraction, but repeated treatment also increases processing time and can eventually become counterproductive. Louka *et al*. (2004) [15] and other studies have shown that pressure, cycle number and material condition need to be considered together rather than as isolated variables.

Vacuum level and decompression rate are also important. A rapid pressure drops favours flash evaporation and expansion, while a slower decompression may produce a different structural response. For this reason, DIC optimization is normally a product specific exercise involving pressure, time, moisture content, cycle number and pressure drop conditions rather than a single universal setting. (Louka *et al*., 2004 [15]; Hamoud-Agha and Allaf, 2019 [9])

DIC for Drying and Swell Drying

It is useful to distinguish between DIC used directly for drying and DIC used as a drying pretreatment. In some processes, the rapid pressure drop contributes to moisture removal, while in others it mainly modifies the structure before a separate hot air, vacuum, heat pump or other drying step. This makes DIC useful for intensifying drying without necessarily replacing the existing dryer. (Pech-Almeida *et al*., 2021 [17]; Cheng *et al*., 2024 [6])

The improvement in drying is closely associated with changes in effective moisture diffusivity. Expansion creates larger and more interconnected pores, providing easier pathways for water to move toward the surface. Thus, although DIC may not remove all the moisture during the pressure drop, it can make the remaining moisture easier to remove during subsequent drying. (Hamoud-Agha and Allaf, 2019 [9]; Pech-Almeida *et al*., 2021 [17])

The expanded structure can also improve rehydration. The newly formed pores allow water to penetrate the dried material more easily, reducing the time required to regain moisture. For fruits and vegetables, this improved rehydration can be an important quality advantage along with faster drying. (Li *et al*., 2020 [13]; Pech-Almeida *et al*., 2021 [17])

Texture is another important outcome of swell drying. Uniform expansion can produce a light and porous structure with desirable crispness, whereas uneven expansion may result in cracks or excessive brittleness. The final texture therefore depends on the moisture level, treatment intensity and characteristics of the raw material. (Kaur *et al*., 2023 [11]; Gao *et al*., 2022 [7])

Drying is one of the major applications of DIC (Mounir *et al*., 2012 [16]; Pech-Almeida *et al*., 2021 [17]). During conventional hot air drying, moisture moves from the interior to the surface before being removed by the surrounding air. Shrinkage can reduce pore spaces and slow moisture movement, particularly during the later stages. DIC addresses this limitation by creating structural changes before or during drying. (Hamoud-Agha and Allaf, 2019 [9]; Pech-Almeida *et al*., 2021 [17])

In swell drying, also referred to as explosion puff or expansion puff drying, a partly dried material is subjected to rapid decompression. The sudden pressure reduction causes internal water to vaporize and expands the material, forming pores that provide shorter pathways for moisture movement. This can increase effective diffusivity, reduce the remaining drying time and produce a lighter, more porous product. (Hamoud-Agha and Allaf, 2019 [9])

DIC can also be integrated with other drying methods. For example, hot air may be used for initial moisture removal,

followed by DIC to open the structure and accelerate the later drying stage. Recent studies have also explored DIC as a pretreatment for heat pump drying, showing that it can be incorporated into existing drying systems rather than completely replacing them. (Cheng *et al*., 2024 [6]; Pech-Almeida *et al*., 2021 [17])

DIC and Quality Preservation

Nutritional quality should be considered along with the physical changes caused by DIC. Vitamins, antioxidants and other sensitive compounds may be affected by temperature and treatment time. Although shorter thermal exposure can help reduce losses, the response depends on the compound and food matrix. Therefore, retention should be measured rather than assumed to improve simply because processing is faster. (Pech-Almeida *et al*., 2021 [17]; Hamoud-Agha and Allaf, 2019 [9])

DIC can also influence the availability of bioactive compounds. Structural disruption may make compounds within the plant matrix easier to extract, while prolonged heating may cause their degradation. Hence, higher measured levels after DIC may reflect improved extractability rather than the formation of new compounds. (Amor and Allaf, 2009 [3]; Pech-Almeida *et al*., 2021 [17])

Colour is an important indicator of quality during drying. Changes in *L**, *a** and *b** values can help identify browning, pigment loss and structural changes that may not be easily noticed visually. Since DIC can influence both pigment stability and light scattering through structural expansion, colour should be assessed experimentally along with sensory observations. (Gao *et al*., 2022 [7]; Pech-Almeida *et al*., 2021 [17])

Texture is similarly affected by the degree of expansion and subsequent drying. DIC may produce a lighter, more porous structure with improved crispness or rehydration, but excessive expansion can result in brittleness or a weak structure. Hardness, fracture behaviour and rehydration should therefore be considered together, as the final texture depends on product composition, moisture content and treatment severity. (Kaur *et al*., 2023 [11]; Gao *et al*., 2022 [7])

Overall, the quality benefits of DIC are mainly related to reducing prolonged thermal exposure while creating useful structural changes. However, DIC is not automatically protective; appropriate pressure, temperature and treatment time are needed to achieve the desired nutritional, colour and textural quality. (Hamoud-Agha and Allaf, 2019 [9]; Gao *et al*., 2022 [7])

Applications of DIC in Explosion Puff Drying and Yam Processing

Gao *et al*. (2022) [7] compared explosion puff drying (EPD) with air drying, vacuum drying and freeze drying for yam chips. Their study showed that drying performance cannot be judged only by final moisture content, as products with similar moisture levels can still differ in pore structure, crispness, rehydration and sensory quality. The rapid pressure release during EPD produced an expanded porous structure that influenced these properties.

The EPD treated yam showed improved crispness and rehydration, which were associated with the formation of an open internal structure. The study also reported favourable retention of vitamin C and total polyphenols compared with some conventional drying methods. These results indicate that structural modification combined with shorter thermal exposure can help maintain important quality characteristics. (Gao *et al*., 2022 [7])

Aroma compounds are another important quality aspect in yam processing. Prolonged heating can cause the loss or alteration of volatile compounds, whereas the rapid nature of EPD may help retain a wider range of aroma related compounds. The differences observed in volatile profiles were also reflected in sensory characteristics, showing the value of combining instrumental and sensory evaluation. (Gao *et al*., 2022 [7])

The comparison with conventional drying methods also highlights the different advantages and limitations of each technology. Freeze drying can provide high quality products but generally requires greater energy and specialized equipment, while air and vacuum drying operate under different thermal and structural conditions. EPD offers an alternative approach by combining rapid decompression with structural expansion, making it relevant where product quality, processing time and energy use need to be considered together. (Gao *et al*., 2022 [7]; Kaur *et al*., 2023 [11])

Application of DIC in Oilseed Pretreatment and Soybean Oil Extraction

Oil extraction is largely a mass transfer process, as oil is trapped within the cellular structure of the seed. DIC can be used as a pretreatment to disrupt this structure and improve the accessibility of oil during subsequent extraction. In soybean processing, the pressure drop creates structural openings that can facilitate solvent movement into the material and the release of oil from the matrix. (Jablaoui *et al*., 2020 [10]; Pech-Almeida *et al*., 2021 [17])

Jablaoui *et al*. (2020) [10] investigated DIC pretreatment before solvent extraction of soybean oil and compared it with conventional expander processing. The treatment produced a more open and porous structure, as observed microscopically, which helped improve contact between the solvent and oil containing regions. This structural modification enhanced mass transfer and contributed to improved oil recovery and a shorter extraction period.

The study demonstrates that DIC can function as a process intensification step rather than replacing the extraction process itself. The existing solvent extraction and separation stages can be retained, while DIC is introduced before extraction to improve raw material accessibility. This approach may make the technology easier to integrate into existing processing systems. (Jablaoui *et al*., 2020 [10]; Pech-Almeida *et al*., 2021 [17])

DIC may also offer advantages in maintaining oil quality because the treatment is relatively short compared with prolonged heating. However, further studies are needed to assess its effects on oxidation stability, minor oil components, solvent consumption and overall processing cost. Improved yield and faster extraction would need to provide sufficient benefits to justify the additional equipment and operating requirements. (Jablaoui *et al*., 2020 [10])

Applications of DIC for Extraction of Bioactive Compounds and Essential Oils

Many valuable compounds in plants are located within cells, membranes or other structures that restrict their contact with extraction media. DIC can disrupt these structures by creating pores, cracks and expanded pathways, thereby

improving surface accessibility and reducing resistance to mass transfer. This effect can support the recovery of essential oils, phenolics, flavonoids and other bioactive compounds. (Amor and Allaf, 2009 [3]; Pech-Almeida *et al*., 2021 [17])

For essential oils, DIC induced expansion can expose internal oil containing structures and improve contact with the extraction medium. The treated material may also become more porous and brittle, making subsequent grinding or extraction easier. However, treatment intensity must be controlled because excessive heat or pressure exposure may damage sensitive compounds. (Amor and Allaf, 2009 [3]; Hamoud-Agha and Allaf, 2019 [9])

DIC has particular potential for extracting valuable compounds from agricultural residues such as peels, stalks and pomace. These materials are often available in large quantities but have limited value before processing. Improving the recovery of antioxidants, pigments and other phytochemicals can therefore support waste valorization and the development of higher value products. (Chemat *et al*., 2012 [4]; Chemat *et al*., 2017 [5])

Louati *et al*. (2019) [14] demonstrated this potential using orange processing by products, where DIC assisted treatment improved the accessibility and recovery of compounds including hesperidin, rutin, flavones and naringin. Similarly, Sánchez-Valdepeñas *et al*. (2015) [19] investigated DIC assisted extraction from grape stalks and reported recovery of phenolic compounds. These studies show how structural modification by DIC can improve the use of agricultural by products as sources of valuable bioactive compounds while potentially reducing the severity or duration of subsequent extraction steps.

Applications of DIC in Microbial Decontamination and Reduction of Anti Nutritional Compounds

DIC has been investigated as a method for reducing microbial contamination in solid and powdered foods. The process combines short steam heating with rapid decompression, which can damage microorganisms and reduce their numbers. However, the effectiveness depends on factors such as the target organism, product composition, moisture content, temperature and treatment time. Therefore, microbial safety must be validated for each specific food and processing condition rather than being attributed to pressure release alone. (Allaf *et al*., 2011 [2]; Pech-Almeida *et al*., 2021 [17])

Powdered foods require particular attention because microorganisms may not be distributed evenly throughout the material. Steam penetration, moisture availability, particle arrangement and reactor conditions can influence the treatment received by individual particles. These factors become especially important when transferring DIC from laboratory to larger scale processing. (Allaf *et al*., 2011 [2])

DIC has also been studied for reducing anti nutritional compounds such as trypsin inhibitors, phytates, glucosinolates and alkaloids. The response varies with the chemical nature and location of each compound, so a treatment effective against one anti nutritional factor may not produce the same effect on another. Haddad and Allaf (2007) [8] showed that controlled DIC treatment can modify selected anti nutritional components while also altering the physical structure of plant materials.

An important advantage of DIC is that microbial reduction and modification of anti nutritional factors can potentially occur alongside other processing benefits such as drying and structural expansion. However, treatment conditions need to be carefully optimized to achieve the desired reduction without causing unnecessary quality losses. (Allaf *et al*., 2011 [2]; Haddad and Allaf, 2007 [8])

Applications of DIC in Waste Valorization and Green Extraction

Food and agricultural industries generate residues such as peels, seeds, stalks and pomace that may still contain valuable compounds. DIC can modify the structure of these materials, making them more permeable and improving the recovery of phenolics, antioxidants and other useful constituents. This approach can increase the value obtained from existing biomass while reducing the amount treated as waste. (Chemat *et al*., 2012 [4]; Chemat *et al*., 2017 [5])

Orange peels and grape stalks are examples of residues that have been investigated for DIC assisted valorization. Louati *et al*. (2019) [14] reported improved accessibility of bioactive compounds from orange processing residues, while Sánchez-Valdepeñas *et al*. (2015) [19] demonstrated the potential of DIC assisted extraction of phenolic compounds from grape stalks. These findings suggest that structural modification can improve extraction efficiency and may reduce the severity or duration of subsequent processing.

DIC can also support non-food applications. Romero-Cano *et al*. (2016) [18] used DIC treated orange peel to produce a biosorbent for removing Cu (II) and phenol. This example shows that the structural changes created by DIC can be useful beyond food preservation and extraction, particularly in environmental applications.

The technology also fits within the broader concept of green extraction. Improving mass transfer may reduce solvent consumption, processing time and energy requirements, although DIC itself does not automatically make a process environmentally friendly. It can also be combined with techniques such as ultrasound, microwave treatment or heat pump drying, depending on the raw material and the desired product. (Chemat *et al*., 2012 [4]; Chemat *et al*., 2017 [5]; Cheng *et al*., 2024 [6])

Advantages of DIC Technology

DIC offers greater flexibility than conventional drying because its operating conditions can be adjusted according to the desired final product. Higher expansion may be suitable for snack products, while moderate structural changes may be preferred for rehydratable foods or extraction applications. This adaptability allows the treatment to be tailored to different raw materials and product requirements. (Allaf and Allaf, 2014 [1]; Pech-Almeida *et al*., 2021 [17])

A major advantage of DIC is its potential to shorten drying time by creating a porous structure that facilitates moisture movement. Reduced processing time can improve production capacity, although the overall benefit should be assessed by considering steam generation, vacuum requirements and any additional drying stages. (Hamoud-Agha and Allaf, 2019 [9]; Pech-Almeida *et al*., 2021 [17])

The rapid pressure drop can also provide several effects within a single treatment, including structural expansion, improved drying and greater accessibility for subsequent extraction. Rapid cooling after decompression may further limit prolonged heat exposure, while the resulting porous structure can improve crispness and rehydration. Depending

on the product and processing conditions, these effects may also help retain selected nutrients and bioactive compounds. (Gao *et al*., 2022 [7]; Pech Almeida *et al*., 2021 [17])

Overall, DIC is best considered a process intensification technology rather than simply an alternative drying method. Its value is greatest when the structural changes produced during treatment provide additional benefits in later processing, such as faster drying, improved rehydration or enhanced extraction. (Pech-Almeida *et al*., 2021 [17]; Jablaoui *et al*., 2020 [10])

Limitations and Challenges

Although DIC offers several advantages, its industrial use involves equipment and operating challenges. The system requires pressure resistant vessels, steam generation, vacuum capacity and reliable pressure control components. Repeated pressure changes can also place demands on valves and other mechanical parts, while regular cleaning and sanitation are essential for food applications. (Allaf and Allaf, 2014 [1]; Hamoud-Agha and Allaf, 2019 [9])

Scale up is another important concern. Product loading, chamber geometry, steam distribution and decompression rate can affect treatment uniformity. Conditions that work well with small laboratory samples may not provide the same temperature, moisture and expansion throughout a larger batch. Therefore, pilot scale trials and process modelling are useful when transferring DIC from laboratory to industrial operation. (Pech-Almeida *et al*., 2021 [17]; Allaf and Allaf, 2014 [1])

DIC performance also varies considerably with the raw material. Differences in moisture content, composition, cellular structure and thermal sensitivity mean that a single set of pressure and time conditions cannot be applied universally. Process conditions must therefore be optimized for each product to obtain the desired structural and quality changes. (Pech-Almeida *et al*., 2021 [17]; Louka *et al*., 2004 [15])

Economic feasibility is another factor that needs careful consideration. Equipment costs, steam generation, vacuum operation and maintenance should be evaluated together with processing time, product yield and quality improvements. Similarly, environmental performance should be assessed across the complete process, including pre-drying and downstream extraction, rather than considering the DIC stage alone. (Chemat *et al*., 2012 [4]; Chemat *et al*., 2017 [5]; Hamoud-Agha and Allaf, 2019 [9])

Finally, applications involving microbial decontamination or functional ingredients require appropriate safety and regulatory validation. Overall, successful industrial adoption of DIC depends not only on its technical performance but also on process reliability, economic viability, product quality and total resource use.

Conclusion

Instant Controlled Pressure Drop (DIC) represents an innovative processing approach in which a brief steam treatment is followed by a sudden reduction in pressure. During this rapid decompression, part of the moisture present inside the material is converted into vapour, which can modify and expand the internal structure. These changes can influence several processing characteristics, including moisture removal, extraction efficiency and rehydration behaviour. Studies conducted on different food materials have demonstrated the potential of DIC for applications such as swell drying, yam processing, soybean oil extraction, recovery of bioactive compounds and microbial decontamination (Pech-Almeida *et al*., 2021 [17]; Hamoud-Agha and Allaf, 2019 [9]).

The available literature suggests that DIC can enhance mass transfer and, under optimized conditions, shorten processing time. The relatively brief exposure to high temperature may also help in retaining important quality attributes compared with prolonged thermal treatments. However, successful application of the technology depends on appropriate control of factors such as pressure, treatment duration, moisture content and the rate of decompression. Since different food materials respond differently to pressure and temperature changes, process conditions need to be established according to the characteristics and intended use of each product (Jablaoui *et al*., 2020 [10]; Gao *et al*., 2022 [7]).

Overall, DIC has considerable potential as a process intensification technique for food processing. It can be applied as an independent treatment or combined with conventional drying, extraction or other processing methods to improve overall performance. Further research focusing on scale up, automated process control, energy consumption, economic feasibility and combination with other technologies will be important for its wider industrial application. With suitable process optimization, DIC could contribute to faster and more efficient drying, improved recovery of valuable food components and better utilization of agricultural and food processing resources (Pech-Almeida *et al*., 2021 [17]; Allaf and Allaf, 2014 [1]).

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