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Cold Plasma Treatment Effects on Nutritional Quality and Shelf Life Extension of Fresh-Cut Vegetables

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Abstract--- Minimal processing (peeling, slicing, shredding) breaks tissue, causing the intracellular contents to trigger a wounding response which results in increased respiration and ethylene production, increased enzymatic browning rates, and fast microbial growth, making a product of high nutritional value only last for a few days. It has been proposed that cold plasma may be a promising non-thermal solution to this issue as it is able to inactivate surface microorganisms and oxidative enzymes without raising the temperature of tissues. However, the reactive oxygen and nitrogen species it creates are the very ones that oxidate ascorbic acid, polyphenols and pigments, which has an inherent quality trade-off to the technology, instead of a simple benefit. This review reviews that trade-off quantitatively. Evidence is compiled on the inactivation of polyphenol oxidase (PPO), peroxidase and pectin methylesterase, behaviour of vitamin C, phenolic compounds, chlorophyll and texture, and microbial and shelf-life results obtained in lettuce, rocket, chicory, melon, carrot and apple systems. In the studies reviewed, enzyme inactivation ranged from 42 to 77%, losses of immediate ascorbic acid were generally less than 4–7%, and microbial reductions of 1.7–5 log CFU/g resulted in a shelf life of 2.5–3 days in fresh-cut melon and more than 4 days in ready-to-eat rocket. The pattern is biphasic, that is, a dose response curve with high doses causing a decrease in quality and low doses causing the retention of quality. Hence, the process parameters (gas composition, voltage, exposure mode and time) determine whether cold plasma is a stressor or a preservative, and the paper finds the most important design criteria is to optimize the process parameters according to a multi-parameter quality index rather than the maximum microbial inactivation. This work is concerned with the potential of cold plasma to extend the shelf life and improve nutritional quality of fresh-cut vegetables in the context of polyphenol oxidase (PPO) inactivation, ascorbic acid production, and plasma-activated water application.

Keywords--- Cold Plasma, Fresh-Cut Vegetables, Nutritional Quality, Shelf Life, Polyphenol Oxidase, Ascorbic Acid, Plasma-Activated Water.

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I. Introduction

The fresh-cut sector also exists because consumers like vegetables that, while ready to eat, have not been cooked, and it is limited by the fact that the operations that are used to provide that convenience, reduce the tissue's own defenses (Tappi et al., 2016). Peeling and cutting could also increase ethylene production and thus stimulate respiration and senescence, thereby increasing the rate of vitamin losses. Fresh and fresh-cut products are subject to a short shelf life (a few days) and only have a short distribution period, and the market segment is dominated by a very short shelf life that reduces the market opportunities available for fresh and fresh-cut products and increases the volume of waste. Microbial spoilage is the most important factor limiting the shelf life of fresh and fresh-cut products. The net result is that fresh-cut vegetables are at risk for two failure modes that require different interventions. Microbial spoilage is the safety limit, senescence and enzymatic browning is the quality limit; conventional preservation is attack at the expense of the other. Thermal applications have negative effects, including a reduction in nutritional content (vitamins, phenolic compounds), and losses in physicochemical properties (colour, flavour). Chlorinated washing is widely adopted, inexpensive, but is being increasingly limited by residue issues. Cold plasma has been touted as the solution to this problem and is generally described as a technique used to inactivate microorganisms and enzymes without the use of heat and chemicals. The mechanism is well suited to the surface decontamination as plasma species have short lifetimes and because the treatment does not need to increase the bulk

temperature, which is where microorganisms and enzymes are located. To analysis the gas moisture with contains the microorganisms extended to shelf life of fresh produce with the quality attributes (Pan et al., 2019). A parallel study of fresh green leafy vegetables concludes that cold plasma is one of the sustainable and green processing methods that can achieve the inactivation of the target microorganisms without a noticeable temperature rise during processing and also has great potential in extending the shelf life of perishable and short-shelf-life products. That seems to be an opinion shared by many, but it fails to capture the complexity. Reactive oxygen and nitrogen species in cold plasma (CRONs) directly react with the food matrix to oxidize proteins, lipids, and bioactive compounds and a decrease in nutrients and bioactive compounds such as polyunsaturated fatty acids, sugars, polyphenols, and vitamins has been reported in dairy products, vegetables, fruits and beverages. The impact on dry food products like seeds and nuts is less dramatic, as is illustrative: dry food products damage is dependent on water activity and tissue hydration, which is exactly what fresh-cut vegetables provide in abundance. The question that this paper will attempt to answer is not whether or not cold plasma can extend the shelf life of fresh-cut vegetables but under what conditions this is possible without causing a nutritional penalty, and the dividing line. Section 2 outlines the principles of generation and the chemistry of the reaction processes, Section 3 the plant tissue interaction mechanisms, Section 4, the nutritional implications on a compound-by-compound basis, and Section 5, the microbiological and shelf-life evidence. In Sections 6 and 7 process parameter and delivery format are considered as the design variables which define which regime is entered, and in Sect ions 8 and 9 limitations and research priorities are evaluated.

II. Generation Principles and Reactive Chemistry

Cold plasma is a semi- or fully ionized gas that forms an ensemble of other active species (atoms, charged particles, free radicals, low- and high-energy electrons and UV photons) with the electrons being the most important active species to produce the reactive ones. The high electron temperature and low bulk gas temperature result in a possibility of using the discharge for the heating of heat sensitive biological material without thermal damage. Four different discharge configurations are prevalent in the fresh produce literature. Dielectric barrier discharge applies the specimen between the electrodes with an insulating barrier in between, and it can be created in a closed package with the ambient air. By directing the flowing gas stream through a discharge and out through a nozzle, atmospheric pressure plasma jets provide a small treatment volume and a short duration of treatment, making them ideal for small objects or brief exposure. In one study, liquid-cathode air discharge was used to generate water which was then activated by corona discharge. In this study, water was generated by a liquid-cathode air discharge and activated by corona discharge. The discharges from the microwave are high power densities for short exposure times like in a 2.45 GHz system with 900 W operated for 10 min in nitrogen. The reactive chemistry consists of a combination of oxygen and/or nitrogen species with varying composition depending on the feed gas. If the aim is to retain the vitamins, the ozone burden is negative, because the generated ozone may be able to lower the content of ascorbic acid in the vitamin-C-enriched fruit product, and therefore working conditions which produce high amounts of ozone should be avoided to the greatest extent possible when handling vitamin-C-enriched fruit products (Zhang et al., 2022). Nitrogen has been examined as the working gas when oxidative damage to tissue is an issue and, in one in-package study of lettuce, reduced E. coli and Salmonella by 2.9 and 2.2 log, respectively, by applying N_2 at 900 W for 10 min. The discharge produces the reactive species that then dissolve in the water to react is an important variant which produces plasma-activated water. The method enables the producer to save the damage of the cells due to direct exposure to cold plasma and it is a valuable alternative for several products for the current washing during fresh-cut processing. The plasma activated water is applied by immersion or spraying, which means that it reaches the entire surface of the leaf, even the cut edges and interstices that are inaccessible to the directional jet; the plasma activated water washing of rocket leaves has been carried out for 2 min, 5 min, 10 min and 20 min.

III. Mechanisms of Action on Plant Tissue

3.1 Enzyme Inactivation

The most well documented quality impact of cold plasma on fresh cut vegetables is the inhibition of oxidative and cell wall degrading enzymes. The effects on polyphenol oxidase, peroxidase and pectin methyl esterase, which are known to control browning, lignification and softening respectively, are consistently reported in the literature. Direct evidence is strong evidence. Inhibition of polyphenol oxidase activity was

directly related to the duration of exposure in plasma, reaching up to 57% inhibition for 30 min treatment in apple slices. The residual activity of PPO was reduced by 42% in freshly cut apples after 10, 20 and 30 min exposure to microwave plasma while the same freshly cut apples and potatoes were exposed to microwave plasma for 10 min, the respective reductions to the residual activity of PPO were 62% and 77% (Tappi et al., 2018). To analysis the oxidation with reactive side changed through secondary protein with modification of amino acid with enzyme. All enzymes respond and the variation is informative. Peroxidase and pectinmethylesterase activities were only slightly inhibited in fresh-cut melon treated by DBD (up to about 17 and 7% respectively) Tappi et al., (2016) and in a similar melon system, residual activities were: 91% after 15 + 15 min of treatment for peroxidase and 82% after 30 + 30 min for pectinmethylesterase, 94% after 30 + 30 min for pectinmethylesterase. The difference in inactivation (57–77% for PPO and < 20% for POD and PME) for the same product classes suggests that plasma inactivation is more likely to occur in the superficial enzyme pool than in the enzymes bound to the tissue matrix, and is consistent with the limited penetration of plasma species.

3.2 Oxidative Modification of Tissue Components

The anthocyanins, lycopene, carotenoids and other pigments in fresh-cut fruits and vegetables are prone to oxidation and can cause darkening of the colour of fresh-cut products. Cell membranes are also being targeted, with 60 min of surface DBD treatment at 6 kV in iceberg lettuce resulting in the highest colour variation and cell damage (Laika et al., 2024). There is another, not so obvious mechanism that can act in the opposite direction. The plasma exposure not only causes passive chemical damage, but also triggers a metabolic response of fresh tissues. Cold-plasma induction results in a strong increase of the activity for 4-coumarate-CoA ligase and chalcone synthetase which leads to higher polyphenol contents in the storage period of fresh-cut apples (Tappi et al., 2018). In other words, the "elicitor" can be low level oxidative stress. This is a mechanistic underpinning of the biphasic nutritional responses outlined in Section 4, and is responsible for the technology's ability to increase polyphenol content in one treatment window and decrease it in the next.

3.3 Physiological Effects

The plasma effect on respiration and ethylene is the most controversial in the literature and is the master variable of post-harvest life. On one hand, the tissue metabolic heat production of fresh-cut melon was found to be proportional to the length of treatment; however, a partial conversion to anaerobic metabolism was noted (Tappi et al., 2016). The rate of Strawberry treat with package among the atmospheric cold level of plasma in 5 min. Which is contains the fruits and vegetables results are decreased with antioxidant activity. This is likely not a contradiction but rather a dose effect. Superficial enzyme inactivation's and a slight reduction in metabolic activity cause a decrease in respiration, while more severe treatments cause a wound response which results in an increase in respiration. Because both responses are noted in similar products, the respiratory rate is a good indicator of whether a particular treatment is in the hermetic or damaging zone.

IV. Effects on Nutritional Quality

4.1 Vitamin C

The most studied, and the most debated nutritional endpoint is ascorbic acid. It is an antioxidant with a relatively high susceptibility to processing because it is prone to redox reactions under processing, and can react directly with the ozone generated in the discharge, which will reduce the vitamin C content (Zhang et al., 2022). The net effects, however, will be dependent on the ratio of oxidative loss to enzymatically promoted regeneration, which is partly a function of dose and partly a function of the metabolic capacity of the product. But, in reality, immediate losses are small. In the literature, no significant change in ascorbic acid content was observed for kiwifruit, but up to 4% decrease was recorded for cut vegetables and fruit like radish sprout and lettuce after plasma treatment and the type of sample, processing time and plasma gas were recorded as critical factors (Zhang et al., 2022). No significant differences were observed in the vitamin C content immediately after DBD treatment for fresh-cut kiwifruit, but vitamin C content decreased by 7% after 4 days of storage. The treatment with the plasma micro-jet at 500 V for 1–8 min led to a decrease of vitamin C, which was 3.6% and 3.2% for pear slices and cucumber and carrot slices, respectively, while the losses were small in absolute terms, they were in the same direction. Cold plasma treatment at 500 V for 0.5-4 s did not increase the intensity of the treatment: Vitamin C content in fresh cut produce decreased. The most impressive regeneration evidence is from storage and not from the immediate post-treatment measurement. DBD cold

plasma-treated blueberries resulted in lower ascorbic acid content at the beginning of the storage period, but the ascorbic acid level in treated samples increased over the control samples after 10 days, possibly due to the increase in dehydroascorbic acid reductase activity due to the active species, which increases the production rate relative to the oxidation rate. The implication for assay design is important, as an assay that is done only at day 0 will systemically underestimate the nutritional effect of plasma treatment, as the main effect may be a slower rate of decline.

4.2 Phenolic Compounds and Antioxidant Capacity

The biphasic response is most apparent in phenolics. The phenolic profile was also significantly affected with increasing plasma treatment time, both quantitatively (increase of 20% after 10 min for fresh-cut Pink Lady apple slices) and qualitatively, and with increasing exposure time, the same trend was observed as the antioxidant activity of the slices, increasing after 10 min and then decreasing with the plasma treatment time (Tappi et al., 2018). That same study found some acidification of the tissue and a decrease in browning following prolonged exposure. This pattern can be repeated in the direction even if the magnitudes are different. The plasma treatment of apple slices for 1 min provided the highest level of antioxidants at the initial day of storage, but did not significantly reduce polyphenol oxidase activity and therefore did not provide long-term stability of the antioxidants during storage. The plasma treatments resulted in a small loss of pigments in fresh-cut kiwifruit, which affected the quality of the product immediately after treatment, but did not alter the amount of pigments in the product at the end of storage. There was no significant difference between treated and control samples in terms of antioxidant content or activity. PPO activity was found to be reduced by 150 W for 30 minutes on fresh-cut apple while antioxidant activity was increased as assessed by DPPH, FRAP and ABTS (Tappi et al., 2018). The pore profile is the other, and often more desirable, profile created by plasma-activated water, as the insult is being delivered in the aqueous phase and at lower intensity. The plasma activated water improved total phenolic contents, antioxidant activity (FRAP, ABTS and DPPH) of fresh cut lettuce at day 7 of storage. The study mainly focused on the DBD treatment along with treatment time related to antioxidant activity for to increase the observed values for to increase the production living cells of AA.

4.3 Pigments, Colour and Texture

The trade-off is most obvious to the consumer in colour, and is where plasma is most obviously multi-modular. Beneficiously, DBD successfully affected the quality maintenance of fresh-cut fruits by enhancing colour maintenance and inhibiting the formation of darkened area in the fruits during storage process, without causing any textural changes in fresh-cut kiwifruit compared with the control. Plasma-activated water was found to greatly inhibit the degradation of lettuce colour (chloriophyll loss) from day 3 of refrigerated storage (Laika et al., 2024). Here mentioned the various types of vegetables followed by tomato, carrot and other types of green leaves are used to treat the plasma activity with water results based on insignificant colour with the changes of fruits and vegetables. On the other hand, the 6 kV in lettuce treatments that reduced PPO and POD also reduced chlorophylls at longer exposure (Laika et al., 2024), and for spinach, the quality declined as a result of surface browning of the in-package treated samples. It's the intensity of treatment – and not the technology itself – that determines which side of the ledger the balance tips. In general, texture does not do as poorly as colour.

There was no significant difference in texture after treatment for strawberry, apple, melons and cherry tomatoes, but a decrease in firmness was reported for blueberry, which was believed to be caused by mechanical damage due to high air-flow rates and temperature increase during the treatment. Firmness loss was negligible in the plasma treated samples of fresh-cut carrots, compared with the firmness loss about 9% in the fresh-cut samples without plasma treatment after 26 days of storage at 1 kVA (Bakla & Bağcı, 2025). The inhibitory effect of cold plasma on the activity of cell wall hydrolases has been blamed for delayed texture degradation and hence decreased production of cellulose, hemicellulose, lignin and pectin. This shows that the gas environment during and after treatments is also a design variable since firmness retention was greater in the 65% O_2 + 16% N_2 + 19% CO_2 environment in table 1.

Table 1: Reported Effects of Cold Plasma on Nutritional and Quality Attributes of Fresh-Cut Vegetables and Related Produce

Produce	Treatment	Nutritional / quality outcome
Fresh-cut iceberg lettuce	Surface DBD, 6 kV, 23 kHz, 15–60 min	PPO and POD reduced, ascorbic acid and antioxidant activity; overall antioxidant activity increase after storage
Fresh-cut lettuce	Plasma-activated water, 1 and 5 min wash, 4 °C	Reduced chlorophyll degradation from day 3; firmness not significantly modified; higher FRAP, ABTS, DPPH and total phenolics at day 7
Fresh-cut Pink Lady apple	Air DBD, up to 30 min	~20% increase in polyphenols at 10 min, progressive decrease thereafter; antioxidant activity increased at 10 min then decreased; PPO inhibition up to 57% at 30 min
Fresh-cut kiwifruit	DBD, 10 and 20 min per side, 4 days storage	Immediate slight pigment loss but better retention during storage; improved colour retention; no textural change; no significant change in antioxidants
Fresh-cut melon	DBD, 15 + 15 and 30 + 30 min, 4 days at 10 °C	POD and PME inhibited by about 17 and 7%; metabolic heat production decreased with treatment duration; POD residual activity 91% and 82%
Fresh-cut carrot	APPJ, 1 kVA, 10–60 s, Ar or dry air, 3 weeks at 4 °C	No significant change in colour (ΔE < 3.0), β-carotene, ascorbic acid, TPC or TAA; firmness retained vs ~9% decline in controls
Cucumber, carrot, pear slices	Plasma micro-jet, 500 V, 1–8 min	Vitamin C reduced by 3.6%, 3.2% and 2.8% respectively; less than 5% moisture loss
Fresh-cut apple	DBD, 150 W, 30 min	PPO reduced, browning incidence reduced, antioxidant activity increased
Fresh-cut apple and potato	Microwave plasma, 10 min	PPO and POD activity reduced by about 62% and 77%

V. Microbial Inactivation and Shelf Life Extension

The microbial argument is more robust and consistent than the nutritional one and is the basis for the technology's market value in table 2. Cold plasma is effective in inactivating bacteria, yeasts and moulds on produce surfaces by disruption of the membrane by charged species, damage of DNA by UV radiation and lipid peroxidation by O3 and peroxynitrite. Reductions reported range from approximately 1 to 5 log CFU/g and are critically dependent on the delivery format. In this section describes the leaves in rockets washed with plasma should activated through the water in 2-5 min with the average reduction of 1.73 log CFU (Laurita et al., 2021). The use of a plasma-treated water as an antimicrobial process-water additive in fresh-cut lettuce washing was effective in reducing the microorganisms by up to 5 $\log_{11}$ cycle; the food quality was not affected by the use of plasma-treated water in the process at both laboratory and pilot scale. The treatment of red chicory for 15 min with DBD resulted in a reduction of L. monocytogenes more than 4 $\log_{10}/cm^2$ and of E. coli more than 5 $\log_{10}$, without affecting colour, freshness and texture, although some losses in odour and overall acceptability were observed during storage. Direct in package treatment is rapid but not as penetrating. The ambient air cold plasma treatment resulted in 30 s for a 7-log reduction in bacterial counts in lettuce broth at 40 kV; on the other hand, to achieve 5 log reduction in biofilm counts on lettuce, the treatment duration was increased to 300 s at 40 kV. The results indicated that on cherry tomatoes, 100 kV, 150 s of DBD treatment reduced E. coli and L. innocua by more than 5 and 3.5 log10 CFU/g, respectively, and up to 3.5 log10 CFU/g of the spoilage microflora, without any significant changes in colour, firmness, pH, or TSS. Static-mode treatment was able to obtain 2.0 and 2.2 $\log_{11}0$ CFU/ml reductions for E. coli on strawberries and spinach, respectively, and 1.3 and 1.7 $\log_{11}0$ reductions for L. innocua on strawberries and spinach, respectively, in a pilot scale open-air DBD system, with no significant differences in colour, firmness, pH and total soluble solids of the vegetables compared to untreated controls (Ziuzina et al., 2020). Reduction to fractions of a log in areas of mild treatment and especially in the context of modified atmosphere packaging. The inactivation rates decreased with MAP with E. coli, with a decrease of 0.6 log CFU/g for Salmonella and 0.8 log CFU/g for L. monocytogenes on lettuce. S. typhimurium was reduced by 1.8 log CFU/g on radish sprouts treated at 900 W for 10 min and began to show signs of wilting after 20 min of treatment. After 15 min, the surviving E. coli

was reduced by 1.35 log per MPN/cm^2 following cold plasma treatment of radicchio. Log reductions are not as meaningful as shelf-life outcomes as they do not account for regrowth and quality decay. In contrast, the longer exposure of 30 + 30 min had no significant effect on the microbial shelf life of fresh-cut melon, the effect being close to that of untreated samples, with the longer treatment likely increasing the susceptibility of the fruit to microbial spoilage, the critical spoilage threshold being reached after 3.5–4 days compared with > 4 days in the 15 + 15 min treated samples (Tappi et al., 2016). The change in colour and texture of leaves was not noticed, and the shelf life was extended from 3 days to 7 days (about 2.5 times) in ready-to-eat rocket salad when plasma activated water was used for 15 min (Laurita et al., 2021). Treatments using plasma technology inhibited browning and enzymatic activities without negatively affecting the freshness and quality of refrigerated fresh-cut fruits and vegetables. It ensured that the quality of apples remained acceptable for 12 days, lowered the presence of E. coli in carrots more than 4 logs within 60 seconds, and prevented spoilage of potatoes and apples for 19 days (Bakla & Bağcı, 2025).

Table 2: Reported Microbial Inactivation and Shelf-Life Outcomes Relevant to Fresh-Cut Vegetables

Produce	Treatment	Microbial outcome	Shelf-life outcome
Fresh-cut melon	DBD, 15 + 15 min, 4 days at 10 °C	Delayed growth of spoilage mesophilic and psychrotrophic microflora	Spoilage threshold beyond 4 days vs spoiled after 2.5–3 days in controls
Rocket leaves	Plasma-activated water, 2–5 min wash	1.7–3 log CFU/g reduction, mesophiles, psychrotrophs, Enterobacteriaceae	3 days extended to 7 days for ready-to-eat rocket salad
Fresh-cut lettuce	Plasma-treated water as washing additive, lab and pilot scale	Up to 5 $\log_{10}$ cycle reduction depending on process variant and scale	Food quality not affected
Fresh-cut lettuce	Plasma-activated water, 1 and 5 min, 4 °C	Strongest inactivation at day 3; psychrotrophs maintained up to seven days	Chlorophyll degradation reduced from day 3
Fresh-cut carrot	APPJ, 1 kVA, ≤60 s, Ar or dry air	>4 log reduction in *E. coli* within 60 s; surface below 50 °C	Firmness retained over 3 weeks at 4 °C
Red chicory	DBD, 15 min	>4 $\log_{10}$ CFU/cm^2 *L. monocytogenes*; >5 $\log_{10}$ *E. coli*	No detrimental effect on colour, freshness, texture
Cherry tomato	DBD, 100 kV, 150 s	>5 and 3.5 $\log_{10}$ CFU/sample *E. coli* and *L. innocua*; up to 3.5 $\log_{10}$ on spoilage flora	No difference in colour, firmness, pH, total soluble solids
Fresh-cut apple and potato	Cold plasma pretreatment	POD and PPO reduced	Stored 19 days without spoilage
Strawberry, spinach (pilot scale)	Open-air DBD, static and continuous	2.0 and 2.2 $\log_{10}$ *E. coli*; 3.8 $\log_{10}$ *L. innocua* on strawberry	Colour, firmness, pH, total soluble solids retained

VI. Process Parameters as Determinants of Outcome

On examination, each of the apparently contradictory results in Sections 4 and 5 turns out to be due to a difference in the parameters of the processes. The same set of elements is mentioned as critical when various technologies are reviewed: the specific characteristics and parameters of the equipment, the physical properties of conducting gas, method of treatment, and intrinsic characteristics of the sample (Pan et al., 2019). The impact of cold plasma is dependent on the parameters: power, frequency, flow rate of the gas, application time, composition of the ionising gas, distance between the electrodes and pressure, as well as the properties of the product. Exposure duration is the most important one because it determines the shift from hormesis to damage. The apple polyphenol data reveal this exactly: an increase of about 20% after 10 min was followed by a gradual reduction of all polyphenol classes at longer exposure times (Tappi et al., 2018). The curve for shelf life of melon indicates a different endpoint – the shorter treatment is effective, while the longer treatment is worthless. The key is that both deactivation of enzymes and oxidation of substrates occur during the reaction and both happen at different rates – the window of opportunity is when the first has gone to some point, but the latter has not. The relative abundances of the reactive species depend on the

composition of the gas. Air and dry air produce ozone and nitrogen oxides, and therefore, strong inactivation with a resulting greater degree of oxidative damage occurs; the handling of vitamin-C containing products in working conditions that produce large amounts of ozone should be avoided (Zhang et al., 2022). Nitrogen and dry air were tested on fresh-cut carrot, with over 4 log reduction of E. coli after 60 s at 900 W for both types of gas (Bakla & Bağcı, 2025). Gas selection is therefore a selectivity lever and not an efficiency lever. The energy density at the sample surface is set by the power, voltage and distance between the electrodes. A 1 kVA jet at nozzle-to-sample distances of 10–40 mm resulted in over 4 log reduction of PPO and POD in lettuce in 60 s with surface temperature remaining below 50 °C Bakla & Bağcı, (2025) while a 6 kV surface DBD exposure required 15–60 min to achieve the same log reduction of PPO and POD in lettuce, with measurable cell damage observed (Laika et al., 2024). The two treatments are not commensurable: one is fast surface decontamination, the other is a long enzymatic one involving an actual oxidative cost. All are modulated by sample and matrix properties. Produce having a waxy cuticle and/or high phenolic content or a large exposed cut surface will react differently than intact tissue and the activity of plasma on PPO in fresh-cut apple have been reported as being strictly cultivar dependent (Tappi et al., 2018). Those reviews have found that the knowledge of how cold plasma affects the quality changes of fresh fruit and vegetables remains limited; and that future research needs to be performed to fully comprehend the mechanisms responsible for the interaction between plasma and food products.

VII. Delivery Formats and Their Consequences

The four commonly used formats have similar physics, with a difference only in intensity and uniformity of the oxidative insult they provide, which is what makes up the nutritional profile. The most thoroughly studied and most likely to give measurable quality changes is direct DBD treatment of unpackaged product in which the discharge impacts directly on the tissue and exposure times are relatively long. As representative, PPO and POD were reduced as a function of the surface treatment time and ozone concentration, while numbers of mesophilic and psychrotrophic bacteria were slightly reduced, yeast counts did not change and the damage caused by the treatment increased in concert with increasing treatment time, with colour variation and decreasing chlorophylls, TPC and ascorbic acid, with antioxidant activity remaining unchanged (Laika et al., 2024). For short, high intensity exposures and products in which browning is the limiting defect, direct treatment is the most suitable. Atmospheric plasma jets provide a directed high intensity treatment over a small area and are suitable for fast decontamination of small items but may be problematic for uniformity of a batch. The results of the carrot study illustrate the positive side of the effects that jets can have; they can reduce the E. coli by over 4 log in 60 s while maintaining surface temperature below 50 °C, and did not significantly affect the colour, β-carotene, ascorbic acid, total phenolics or total antioxidant activity throughout a 3-week storage period (Bakla & Bağcı, 2025). In-package treatment provides a treatment inside the sealed package, which treats the product and changes the package atmosphere at the same time. A great benefit of the cold plasma treatment within the package is that it lowers the risk of contamination occurring immediately after the package sealing, which is a real issue for a product that is not intended to be re-sterilised after packaging. The static mode and continuous mode had an average of 2.0 $\log_{10}$ and 2.2 $\log_{10}$ reduction for E. coli, respectively, and up to 3.8 $\log_{11}$ reduction for L. innocua, in a pilot scale open-air DBD reactor, with no significant difference in colour, firmness, pH or total soluble solids (Ziuzina et al., 2020). The following disadvantages must be noted: Modified atmospheres slow down the inactivation rate; Salmonella (0.6 log CFU/g) and L. monocytogenes (0.8 log CFU/g) had lower inactivation rates in a MA system for lettuce. In-package treatment generally results in moderate log reductions, but with good quality retention, and this is the appropriate balance where the product has a short shelf life due to senescence rather than pathogens. When using the unit operation for fresh-cut vegetables, the best format is plasma activated water, as it is applied by the unit operation. It prevents direct exposure of the cells to cold plasma and washing applications have been reported for green leafy vegetables, fresh-cut apples, blueberries, strawberries, pears, cantaloupe melons, mushrooms, tomatoes, kiwi fruits and red currants. The chemistry should be tracked; with one preparation of plasma-activated water, no measureable NO_2^- concentration was found, and the concentrations of H_2O_2 and NO_3^- were 77.8 and 223.4 mg/L, respectively, and the pH at day 1 was 2.81. The nitrate measurement is not incidental because the concentration of nitrate in the treated tissue was specifically tested as a food quality indicator in the pilot scale lettuce study.

VIII. Limitations and Trade-Offs

8.1 The Biphasic Dose Response

The single greatest restriction is that cold plasma works only in a small range, and not above or below. This is not something you can tune out of; it's a structural aspect of working with a strong oxidant on a living organism. An approximately 20% polyphenol increase after 10 min time, followed by a progressive loss of polyphenols at longer times Tappi et al., (2018) is observed across the endpoints, as is an increase in shelf life from the shorter melon treatment, but not the longer treatment Tappi et al., (2016) and as is firmness loss in blueberries due to mechanical damage from high air-flow rates and temperature rise. The technology requires a product-specific validation as it is not a recipe that can be transferred.

8.2 Penetration and the Survival of Shielded Microorganisms

The action of cold plasma occurs at surfaces. Little penetrating and pathogens can remain in micro-cracks and pores and proliferate during storage and handling. This is the main food-safety rule and is the reason why results of log reductions on inoculated flat test surfaces are frequently higher than those obtained on laboratory-grown three-dimensional leaf structures. It also describes the phenomenon of survival and/or repair of melon after plasma treatment, which was caused by inactivation and/or severe damage caused by plasma treatment, which was then repaired by microbial cells during storage (Tappi et al., 2016). Thus, any claim that would be made for shelf life using day-zero counts is no longer safe, but rather the time to reach a spoilage or safety limit is the correct measurement.

8.3 Byproducts and Residues

Reactive species and free radicals, that may be harmful to human health if they are not controlled, are produced during the use of cold plasma; it is necessary to ensure that the food product is safe for consumption and to reduce possible risks associated with chemical residua or by-products. The selectivity of the process is highly product and process dependent and commercialization must address the fate of all reactive gas species that cannot react with the food, which can be either lost from the process, recaptured and reused, or released within the facility that may pose a risk to personnel.

8.4 Sensory Acceptance, Cost and Regulation

Cold plasma treatment could alter the sensory properties of food, such as colour or flavour, and lead to discolouration or changes in the food texture for sensitive products, so safety, taste and texture of plasma-processed foods may be concerned which remains a barrier for acceptance and perception of plasma-processed products by consumers (Zhang et al., 2022). Economics are not favourable at a small scale, as equipment and process optimisation and personnel training is required and the costs of integrating this technology may be prohibitive for small and medium-sized food manufacturing companies. Regulatory status is uncertain – regulatory status in the EC 315 is uncertain because the evaluation criteria is not well defined, and in the USA, FDA, USDA and EPA regulations may apply, with regulatory steps that are quite variable. Plasma as a minimal-processing approach to fruit is reviewed and it is concluded that the fact that the treatment is not uniform, that there are some operating parameters required, possible effects on fruit quality, the potential for byproduct production and costs are all barriers to its widespread adoption.

IX. Research Priorities

The four gaps are the main restraints to the translation of lab demonstration to industrial line. First, the dose–response relationship needs to be expressed in dosimetric rather than temporal terms. Exposure time is not a good proxy when power, gas or geometry change, leading to apparent conflicting results in the literature: 30 s was enough to achieve a 7-log reduction in broth, while 15 to 60 min was needed to inactivate PPO and POD in another lettuce system (Laika et al., 2024). Studies would be comparable if reporting offered energy density or a measured exposure to reactive species, in addition to time. Secondly, the post treatment course should be assessed and not the immediate effect. In the case of blueberry, the increased ascorbic acid result was initially found, but was followed by an antioxidant superiority result at 10 days Zhang et al., (2022) and in lettuce the increased antioxidant result was found after storage Laika et al., (2024) contrary to the initial result. Usually, 3 time points are collected for each quality attribute for storage. Thirdly there is a need for a composite shelf-life index for the field. An overall evaluation of the real effectiveness of cold plasma technology, in terms of greater stability and durability of the product, will be possible only using a global shelf

life index that takes into account several aspects of food quality—microbiology, physiology, texture, colour and flavour. The number of microbes cannot be used to distinguish between a preserving treatment and a sterilising treatment of a decaying product. Fourth, there is limited research on the use of cold plasma in conjunction with other barriers as compared to their potential value. The plasma treatment was paired with green tea at 5% and exposure time of 60 s which extended the shelf life of fresh-cut dragon fruit by nearly 15 days; therefore, the plasma combined with the modified atmosphere packaging coupled with edible coating and low-temperature storage is the most potential field for application. Existing field studies have already verified that under certain plasma treatment conditions quality attributes are maintained in an acceptable range or even enhanced Pan et al., (2019) and that effects on the physicochemical and organoleptic quality attributes of fresh-cut products have been observed as either being insignificant or negative. The qualified optimism has to be turned into a specification, and this is done through the parametric and dosimetric work described above.

X. Conclusion

The use of cold plasma is a truly useful intervention for fresh-cut vegetables, but it is only useful for certain vegetables and under certain conditions. This microbial reduction is well documented, such as the reduction of 1.7–3 log CFU/g in plasma-activated water washing Laurita et al., (2021), as well as more than 4 $\log_{10}$ in the microbial reduction of pathogens on red chicory and more than 4 log for E. coli on carrot in 60 s on pilot-scale processing (Bakla & Bağcı, 2025). They correspond to documented shelf-life extensions, such as 4 days for the threshold of spoilage vs. 2.5–3 days for fresh-cut melon Tappi et al., (2016); 3 to 7 days for the threshold of acceptability of fresh-cut rocket Laurita et al., (2021); 6 to 12 days for acceptable sensory quality of fresh-cut apple; and 19 days for potato and apple stored without spoilage after pretreatment. The nutritional case is more complicated, more interesting. Vitamins are not just destroyed in the plasma. Losses of ascorbic acid generally are not large (up to 4% across cut fruits and vegetables and 2.8–3.6% in slices of pear, cucumber and carrot) and may even be regained during storage; in the case of blueberries, ascorbic acid levels were higher in treated samples than in controls after 10 days due to greater dehydroascorbate reductase activity(Zhang et al., 2022). Phenolics exhibit reproducible peak levels, increasing by approximately 20% at intermediate exposures due to induction of 4-coumarate-CoA ligase and chalcone synthetase, and then decreasing at longer exposures (Tappi et al., 2018). Plasma-treated lettuce with high dose of plasma keeps its chlorophyll content better from the third day of storage compared to the non-treated sample, and the plasma treatment causes the loss of chlorophyll in the direct high dose treated sample. The common denominator is the mildness of the abiotic stressor, plasma - mild stressor = response, severe stressor = damage. That principle produces operational conclusion. The aim of process design is less to ensure maximum microbial inactivation and more to ensure positioning of the hormetic window for the particular product; this necessitates control of exposure in dosimetric terms, and assessment of quality during storage, not immediately. The microbiological status of treated vegetables should be assessed by a composite measure of the microbiological status, physiology, texture, colour and flavour of the product and not by day-zero counts. Cold plasma will remain a reported preservative and stressor until the time such indices and dosimetry are commonplace—after all, it is both a preservative and a stressor, depending on the dose.

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