ECONOMIC VIABILITY AND EFFICACY OF COLD PLASMA TREATMENT FOR EXTENDING STRAWBERRY SHELF-LIFE AND REDUCING FUNGAL DECAY: A REVIEW

Apoorva Mishra, Pranav Kumar Mishra, Balvir Singh, Riyaz Ahmad

Institute of Agricultural Sciences & Technology, Shri Ramswaroop Memorial University, Barabanki, India

ABSTRACT

Strawberries are highly perishable and vulnerable to microbial spoilage and fungal decay, causing significant post-harvest losses. Traditional preservation methods, such as refrigeration and chemical treatments, have limitations owing to cost, safety, and environmental concerns. Cold plasma, especially atmospheric cold plasma (ACP) generated via dielectric barrier discharge, is emerging as a promising non-thermal, chemical-free alternative for extending the shelf life of food products. ACP can reduce microbial loads by up to 3 log CFU/g, extending the shelf life of strawberries to five days at room temperature and up to nine days under refrigeration, without compromising firmness, color, antioxidants, or phenolic content. It is effective against common pathogens, such as Botrytis cinerea, while maintaining the sensory and nutritional quality of the fruit. Although the initial cost of plasma systems may be high, reduced spoilage and improved quality can offer a good return on investment. Combining ACP with other preservation techniques, such as edible coatings or modified atmosphere packaging, could yield even better results. However, challenges such as large-scale applications, regulatory hurdles, and consumer acceptance must be addressed. In regions such as India, where postharvest losses are high, cold plasma presents a sustainable and efficient preservation method, warranting further research for optimization and broader industry adoption.

KEYWORD

Antimicrobial treatment, Cold plasma, Food preservation, Postharvest technology, Shelf-life extension, Strawberry

1. INTRODUCTION

1.1. Need for Preservation

Strawberry preservation is crucial because of the fruit's high perishability, which leads to significant food waste and economic loss if not properly managed. Strawberries spoil rapidly after harvest because of their delicate structure, high water content, and susceptibility to microbial contamination, making effective preservation essential for maintaining quality, extending shelf life, and ensuring food safety during storage and transport [1].

1.2. Challenges in Extending Shelf-Life

Infrastructure, cost, and consumer concerns regarding food safety and environmental impact often limit traditional methods such as refrigeration and chemical preservatives. Recent research in India has explored innovative solutions, such as nano-zinc oxide and iron oxide formulations, which significantly improve shelf life and quality parameters of strawberries grown in Punjab, suggesting promise for similar climates [2].Edible coatings, especially those incorporating natural antimicrobials or nanomaterials, have emerged as sustainable alternatives that effectively reduce spoilage and maintain fruit quality. Modified atmosphere packaging and biopolymeric films also show potential, but their effectiveness depends on precise gas composition and temperature control, which can be challenging in India's supplychain [3]. While technological advances offer promising strategies, the main challenges remain in adapting these methods to local conditions, ensuring affordability, and maintaining consumer acceptance.

1.3. Overview of Cold Plasma Treatment

Cold plasma treatment is an emerging, non-thermal technology showing promise for extending the shelf life and maintaining the quality of strawberries, including in India, where postharvest losses are significant. Studies using atmospheric cold plasma (ACP) generated by dielectric barrier discharge have demonstrated that in-package plasma treatment can reduce microbial loads on strawberries by 2–3 log cycles, significantly delaying spoilage without adversely affecting key quality attributes such as color, firmness, or nutritional content.[4].ACP-treated strawberries have shown extended shelf life—up to 9 days under refrigeration compared to just 2 days for untreated fruit—while enhancing antioxidant activity and phenolic content.The technology works effectively in different gas atmospheres and can be integrated into modified atmosphere packaging, further improving preservation outcomes. Metabolomic analyses reveal that cold plasma inhibits microbial growth and promotes the biosynthesis of beneficial compounds like flavonoids and phenolics, contributing to improved antioxidant capacity. Cool plasma treatment does not significantly alter the fruit's taste, texture, or appearance, making it suitable for commercial application. While most research has been conducted internationally, the principles and benefits are directly relevant to Indian strawberry production, offering a potential solution to reduce postharvest losses and improve fruit quality for both domestic consumption and export.[5]

2. Cold Plasma Treatment Technology

2.1. Principles of Cold Plasma

Cold plasma technology is a non-thermal process that uses electrical energy to generate a partially ionized gas containing reactive species such as ions, electrons, radicals, and ultraviolet photons, typically at or near room temperature. The core principle involves applying an electric field to a gas (like air, argon, or nitrogen), which excites the gas molecules and creates a plasma rich in reactive oxygen and nitrogen species capable of inactivating microorganisms, degrading pesticides, and modifying food surfaces without significant heat damage.[5], [6] Various plasma generation systems exist, including dielectric barrier discharge, corona discharge, and plasma jets, each producing different types and concentrations of reactive species depending on voltage, frequency, gas type, and flow rate[7]. The antimicrobial action of cold plasma is primarily due to the oxidative stress imposed by these reactive species, which disrupt microbial cell membranes, denature proteins, and damage nucleic acids, making it highly effective for surface decontamination and enzyme inactivation.Because the process is non-thermal, it preserves foods' nutritional and sensory qualities better than traditional heat-based methods. Cold plasma is also used for applications beyond decontamination, such as modifying food functionality, enhancing seed germination, and altering packaging materials. The technology is environmentally friendly, waterless, chemical-free, and energy-efficient[8].Overall, cold plasma represents a promising, sustainable alternative for food processing and safety, with ongoing research focused on optimizing its principles and applications

2.2. Application Methods for Strawberries

Cold plasma technology is increasingly used for decontaminating and preserving strawberries, employing several application methods that prioritize microbial safety and fruit quality. The most common approach is in-package treatment, where strawberries are sealed in containers and exposed to atmospheric cold plasma (ACP) generated by dielectric barrier discharge (DBD) systems; this method effectively reduces bacterial populations, including E. coli, Listeria, and Salmonella, by up to 3–4 log10 CFU, while maintaining key quality attributes such as color, firmness, and antioxidant content during storage.[9], [10]Both static (batch) and continuous modes of ACP have been tested, with continuous treatment showing strong efficacy against pathogens[10].Modified atmospheres (using specific gas mixtures) can be combined with plasma to optimize further decontamination and quality retention[11].Cold plasma can also be applied to fresh-cut strawberries, enhancing their antioxidant capacity and phenolic content by stimulating related metabolic pathways while inhibiting microbial growth[12].Other innovative methods include treating strawberries with cold plasma before or after edible coatings, which can synergistically reduce spoilage and extend shelf life[13].Recent studies also highlight cold plasma's ability to maintain or even enhance aroma and volatile profiles in both fresh and freeze-dried strawberries, making it a versatile tool for postharvest management[14], [15]

2.3. Advantages Over Traditional Preservation Techniques

Cold plasma offers several advantages over traditional preservation techniques for strawberries, primarily due to its non-thermal, chemical-free, and water-free nature. Unlike conventional methods such as refrigeration or chemical treatments, cold plasma effectively reduces microbial contamination—including bacteria, yeast, and mold—without compromising the fruit's texture, color, or flavor, and often extends shelf life significantly, sometimes by several days compared to untreated controls[16], [17].It also preserves or even enhances key quality attributes such as firmness, antioxidant activity, and the concentration of beneficial phytochemicals like phenolics, flavonoids, and anthocyanins, which are often lost during traditional storage or thermal processing[18].Additionally, this technology can improve packaging materials, reducing gas exchange and spoilage[19].Unlike some physical methods (e.g., pulsed electric fields), cold plasma does not negatively affect the volatile or metabolomic profile of strawberries, helping to retain their natural aroma and taste[20]Overall, cold plasma stands out as a promising, sustainable alternative for strawberry preservation, offering enhanced safety, quality, and shelf life without the drawbacks of heat or chemical residues.

3. Efficacy of Cold Plasma Treatment

3.1. Impact on Strawberry Shelf-Life

3.1.1. Microbial Reduction

Cold plasma treatment has been shown to significantly extend the shelf life of strawberries by reducing microbial contamination without compromising fruit quality. Studies demonstrate that cold atmospheric plasma (CAP) can reduce total viable microbial counts by approximately 0.9–3 log CFU/g, depending on treatment conditions, and extend shelf-life by several days under refrigerated and room temperature storage compared to untreated controls.[21], [22] In-package plasma treatments are particularly effective, achieving up to 3 log reductions in background microflora and pathogenic bacteria such as E. coli and L. innocua, while maintaining key quality attributes like color, firmness, pH, and soluble solids.[23].

3.1.2. Preservation of Physical Attributes

CAP and plasma-activated water treatments generally do not negatively impact physical qualities such as firmness, color, weight loss, or pH, and in some cases, even help maintain or improve firmness and texture during storage.Additionally, CAP has been found to increase antioxidant activity and phenolic content, contributing to better nutritional quality.[24].

3.1.3. Maintenance of Nutritional Quality

Cold plasma treatment either preserves or increases key nutritional components such as phenolic compounds, flavonoids, anthocyanins, and antioxidant activity, with some reports noting increases of up to 20% in phenolics and 16% in antioxidant activity[25].Plasma-activated water, a related approach, also delays quality deterioration and preserves vitamin C and antioxidant capacity[26].The treatment does not significantly affect important quality parameters like firmness, color, pH, or total soluble solids; in some cases, it helps maintain texture and volatile profiles during storage.[27]

3.1.4. Fungal decay prevention

Cold plasma treatment has shown significant efficacy in preventing fungal decay in strawberries by reducing the microbial load, including yeasts and moulds, and extending shelf-life without compromising fruit quality.[28].The technology works by generating reactive oxygen and nitrogen species (RONS) that disrupt fungal cell walls, membranes, and metabolic processes, leading to cell death and inhibition of spore germination[29].Studies have demonstrated that cold plasma can reduce the incidence of common strawberry pathogens such as Botrytis cinerea, a significant cause of postharvest decay, and can also inactivate other fungi like Aspergillus and Penicillium, which are known for producing harmful mycotoxins[30].The mechanism involves direct oxidative damage to fungal structures and indirect effects through plasma-activated water or air, which generate antifungal agents after treatment. Additionally, cold plasma treatment can enhance the accumulation of phenolic compounds and antioxidants in strawberries, further contributing to resistance against fungal infection and improving nutritional quality[31]. Cold plasma treatment can also enhance the accumulation of phenolic compounds and antioxidants in strawberries, further contributing to resistance against fungal infection and improving nutritional quality.

3.2. Comparison with Other Preservation Methods

Cold plasma has demonstrated effective inactivation against many microorganisms, often surpassing traditional disinfection methods in certain aspects. Cold plasma has shown particular efficacy against antibiotic-resistant bacteria, a significant concern in healthcare settings. For example, it effectively inactivated methicillin-resistant Staphylococcus aureus (MRSA) and Pseudomonas aeruginosa, with efficacy comparable to antibiotics but exhibiting a quicker killing rate [32]. The technology also proved highly effective against antibiotic-resistant Escherichia coli in wastewater, achieving over 99.999% reduction [33].Interestingly, cold plasma has shown promise in inactivating vegetative bacteria and bacterial spores, typically more resistant to traditional disinfection methods. A study demonstrated that a plasma microjet effectively inactivated both vegetative bacteria and spores within the area of plasma exposure [34]. Additionally, cold plasma has been found effective against viruses, with the ability to inactivate various types on surfaces, in water, or aerosols [35]. Cold plasma shows broad-spectrum antimicrobial activity but appears particularly effective against antibiotic-resistant bacteria, bacterial spores, and viruses. Its ability to target multiple cellular components simultaneously (membrane, enzymes, DNA) [36]It is a promising alternative to traditional disinfection methods, especially for microorganisms resistant to conventional treatments. Cold plasma's unique combination of physical and chemical mechanisms, including generating reactive species and UV radiation, allows it to effectively inactivate a wide range of microorganisms without the limitations of traditional thermal or chemical methods. This makes it a promising technology for various applications, including food preservation, medical device sterilization, and environmental decontamination [37], [38], [39].

4. Economic Viability

Cold plasma treatment has shown promising results for decontamination and shelf-life extension of strawberries. However, its economic viability needs careful consideration:Implementation costs for atmospheric cold plasma (ACP) systems can be significant, requiring specialized equipment for generating plasma and controlling gas mixtures. However, the technology allows for in-package decontamination, which can prevent post-processing contamination and potentially reduce overall costs [40]. The initial investment in ACP systems must be weighed against potential long-term benefits.

From a cost-benefit perspective, ACP treatment has demonstrated effectiveness in reducing microbial loads and extending shelf-life of strawberries. Studies have shown that ACP can extend strawberry shelf-life to 5 days at room temperature and 9 days under refrigeration, compared to 2 days for untreated fruit [41]. This significant extension in shelf-life could translate to reduced food waste and increased marketability, potentially offsetting implementation costs. Additionally, ACP treatment has been found to maintain or even enhance specific quality attributes of strawberries, such as antioxidant activity and phenolic content [42] , which could add value to the product.

Scalability considerations present challenges and opportunities for cold plasma technology in strawberry processing. While the technology has shown efficacy in laboratory settings, scaling up to industrial levels may require significant engineering and process optimization. Concerns about the safety, active life, and environmental impact of reactive gas species generated by cold plasma need to be addressed [43] . Additionally, regulatory approval processes may require substantial data demonstrating efficacy and safety at scale [43] .

While cold plasma technology shows promise for improving strawberry quality and shelf-life, its economic viability will depend on balancing implementation costs against potential benefits in reduced waste, extended marketability, and maintained fruit quality. Further research and development are needed to address scalability challenges and regulatory requirements before widespread industrial adoption can be realized.

5. Regulatory and Safety Consideration

From a food safety perspective, cold plasma treatment has shown effectiveness in microbial decontamination and pest control (Cullen et al., 2018). It can significantly reduce the background microflora of strawberries by approximately 3.0 log cycles in 300 seconds of in-package treatment [45] . This demonstrates its potential as a food safety intervention. However, regulatory approval remains a significant challenge for the adoption of atmospheric plasma as a food processing tool [46]. The lack of consensus on international standards and divergent national regulations on food safety technologies can be costly and impact trade [47] .

Consumer acceptance is crucial for successfully implementing any new food processing technology. Cold plasma treatment has shown promising results in improving the aroma of freeze-dried strawberries, which could enhance consumer acceptance [48] However, the impact of cold plasma on sensory properties, particularly color, which is an important parameter for consumer acceptance, needs further assessment [49] . Additionally, concerns about safety and consumer acceptance of treated food need to be addressed [50].

Regarding environmental impact, cold plasma technology is considered environmentally friendly due to its low running cost and operational simplicity [51]. It aligns with the food industry's need to embrace emerging technologies to achieve sustainable food production, potentially reducing energy consumption and waste [52].However, the environmental impact of large-scale implementation and any potential adverse effects need to be thoroughly evaluated to ensure regulatory approval and consumer acceptance [51] .

While cold plasma technology shows promise for preserving strawberries, addressing regulatory approval, ensuring consumer acceptance, and thoroughly assessing its environmental impact are crucial before widespread adoption in the food industry.

6. FUTURE PROSPECTS AND RESEARCH DIRECTION

Optimization of treatment parameters is crucial for maximizing the effectiveness of cold plasma while minimizing any negative impacts on fruit quality. Studies have shown that factors such as gas mixture composition, treatment time, and applied voltage can significantly affect microbial inactivation and fruit quality [45], [53]. Future research should focus on fine-tuning these parameters to achieve optimal results for strawberry preservation.

Combining cold plasma with other preservation techniques offers exciting possibilities. For instance, integrating cold plasma with edible coatings or modified atmosphere packaging could potentially enhance its effectiveness and extend shelf life further [50], [54]. Research on synergistic effects between cold plasma and other methods, such as Aloe vera gel coating with essential oils, could lead to innovative preservation strategies [54] .

The potential applications of cold plasma extend beyond strawberries to other perishable fruits. Its ability to inactivate microorganisms and enzymes without heat makes it suitable for various fruits sensitive to thermal treatments [55], [56]. However, more research is needed to understand the specific effects of cold plasma on different fruit matrices and to optimize treatment conditions for each fruit type.

Key areas for future investigation include optimizing treatment parameters, exploring combination treatments, and expanding applications to a broader range of fruits. Additionally, addressing challenges such as potential chemical interactions with food components and scaling up the technology for commercial use will be crucial for its widespread adoption in the food industry [56], [57]

7. CONCLUSION

Cold plasma technology presents a compelling and sustainable solution for extending the shelf life and preserving the quality of strawberries. The treatment has proven effective in significantly reducing microbial and fungal contamination, maintaining key physical and nutritional attributes, and enhancing antioxidant activity. Compared to traditional preservation methods, cold plasma stands out for its non-thermal, chemical-free approach that maintains sensory qualities without compromising safety or nutritional value.

Economically, while initial investment in cold plasma systems may be substantial, the long-term benefits—including reduced postharvest losses, extended marketability, and added product value—offer a favourable cost-benefit balance. However, widespread adoption hinges on overcoming scalability challenges, ensuring regulatory compliance, and addressing consumer acceptance.

Cold plasma offers a viable path forward for the strawberry industry, particularly in regions like India, where postharvest losses are a major concern. It aligns with sustainable agriculture and food safety goals, providing a tool to improve product longevity and quality without resorting to synthetic chemicals or energy-intensive methods.

Future efforts should optimise treatment parameters, explore synergistic preservation strategies, and expand applications across diverse fruit types. Additionally, comprehensive research into large-scale implementation and environmental impact assessments will be essential for regulatory approval and market adoption. With continued innovation and validation, cold plasma has the potential to revolutionize postharvest management in the fruit industry.

ACKNOWLEDGEMENT

I sincerely thank Dr Pranav Kumar Mishra, Assistant Professor, for valuable guidance and support throughout this research. I also acknowledge all teaching and non-teaching staff members of the Department of Horticulture, Shri Ramswaroop Memorial University, Barabanki, Lucknow, for their timely and kind cooperation.

REFERENCES

[1] R. Priyadarshi, A. Jayakumar, C. K. de Souza, J. Rhim, and J. T. Kim, “Advances in strawberry postharvest preservation and packaging: A comprehensive review,” Compr Rev Food Sci Food Saf, vol. 23, no. 4, Jul. 2024, doi: 10.1111/1541-4337.13417.

[2] L. Singh, R. K. Sadawarti, S. K. Singh, V. D. Rajput, T. Minkina, and S. Sushkova, “Efficacy of nano-zinc oxide and iron oxide formulations on shelf life of strawberry,” EURASIAN JOURNAL OF SOIL SCIENCE (EJSS), vol. 13, no. 3, pp. 254–262, May 2024, doi: 10.18393/ejss.1484756.

[3] E. Paulsen, S. Barrios, N. Bogdanoff, G. C. Leandro, and G. A. Valencia, “Recent Progress in Modified Atmosphere Packaging and Biopolymeric Films and Coatings for Fresh Strawberry Shelf-Life Extension,” Packaging Technology and Science, vol. 37, no. 7, pp. 619–640, Jul. 2024, doi: 10.1002/pts.2817.

[4] N. N. Misra et al., “In-package atmospheric pressure cold plasma treatment of strawberries,” J Food Eng, vol. 125, pp. 131–138, Mar. 2014, doi: 10.1016/j.jfoodeng.2013.10.023.

[5] S. Rana, D. Mehta, V. Bansal, U. S. Shivhare, and S. K. Yadav, “Atmospheric cold plasma (ACP) treatment improved in-package shelf-life of strawberry fruit,” J Food Sci Technol, vol. 57, no. 1, pp. 102–112, Jan. 2020, doi: 10.1007/s13197-019-04035-7.

[6] A. K. Deshmukh, G. Talwar, and M. Singla, “Cold plasma technology – An overview of basics and principle,” Environ Conserv J, vol. 23, no. 3, pp. 87–101, Dec. 2022, doi: 10.36953/ECJ.8722147.

[7] P. J. Cullen, “Systems for Generation of Cold Plasma,” in Applications of Cold Plasma in Food Safety, Singapore: Springer Singapore, 2022, pp. 37–46. doi: 10.1007/978-981-16-1827-7_2.

[8] M. E. Oner, B. Gultekin Subasi, G. Ozkan, T. Esatbeyoglu, and E. Capanoglu, “Efficacy of cold plasma technology on the constituents of plant-based food products: Principles, current applications, and future potentials,” Food Research International, vol. 172, p. 113079, Oct. 2023, doi: 10.1016/j.foodres.2023.113079.

[9] N. N. Misra et al., “In-package atmospheric pressure cold plasma treatment of strawberries,” J Food Eng, vol. 125, pp. 131–138, Mar. 2014, doi: 10.1016/j.jfoodeng.2013.10.023.

[10] D. Ziuzina et al., “Investigation of a large gap cold plasma reactor for continuous in-package decontamination of fresh strawberries and spinach,” Innovative Food Science & Emerging Technologies, vol. 59, p. 102229, Jan. 2020, doi: 10.1016/j.ifset.2019.102229.

[11] N. N. Misra et al., “Cold Plasma in Modified Atmospheres for Post-harvest Treatment of Strawberries,” Food Bioproc Tech, vol. 7, no. 10, pp. 3045–3054, Oct. 2014, doi: 10.1007/s11947-014-1356-0.

[12] M. Li, X. Li, C. Han, N. Ji, P. Jin, and Y. Zheng, “Physiological and Metabolomic Analysis of Cold Plasma Treated Fresh-Cut Strawberries,” J Agric Food Chem, vol. 67, no. 14, pp. 4043–4053, Apr. 2019, doi: 10.1021/acs.jafc.9b00656.

[13] Z. A. Belay, N. E. Nyamende, and O. J. Caleb, “Impact of cold plasma-mediated treatment on coated and packaged ‘Monterey’ strawberries during cold storage,” South African Journal of Plant and Soil, vol. 39, no. 4, pp. 302–307, Oct. 2022, doi: 10.1080/02571862.2022.2104946.

[14] M. Giannoglou et al., “Effect of cold atmospheric plasma and pulsed electromagnetic fields on strawberry quality and shelf-life,” Innovative Food Science & Emerging Technologies, vol. 68, p. 102631, Mar. 2021, doi: 10.1016/j.ifset.2021.102631.

[15] A. Zárate-Carbajal, E. A. Lagarda-Clark, S. Mikhaylin, and A. Duarte-Sierra, “Untargeted metabolomic analysis of strawberries exposed to pulsed electric fields and cold plasma before postharvest storage,” Future Foods, vol. 9, p. 100364, Jun. 2024, doi: 10.1016/j.fufo.2024.100364.

[16] Z. A. Belay, N. E. Nyamende, and O. J. Caleb, “Impact of cold plasma-mediated treatment on coated and packaged ‘Monterey’ strawberries during cold storage,” South African Journal of Plant and Soil, vol. 39, no. 4, pp. 302–307, Oct. 2022, doi: 10.1080/02571862.2022.2104946.

[17] D. Ziuzina et al., “Investigation of a large gap cold plasma reactor for continuous in-package decontamination of fresh strawberries and spinach,” Innovative Food Science & Emerging Technologies, vol. 59, p. 102229, Jan. 2020, doi: 10.1016/j.ifset.2019.102229.

[18] M. Giannoglou et al., “Effect of cold atmospheric plasma and pulsed electromagnetic fields on strawberry quality and shelf-life,” Innovative Food Science & Emerging Technologies, vol. 68, p. 102631, Mar. 2021, doi: 10.1016/j.ifset.2021.102631.

[19] M. Rashvand et al., “Effect of Dielectric Barrier Discharge Cold Plasma on the Bio-nanocomposite Film and its Potential to Preserve the Quality of Strawberry under Modified Atmosphere Packaging,” Food Bioproc Tech, vol. 17, no. 5, pp. 1247–1264, May 2024, doi: 10.1007/s11947-023-03196-w.

[20] A. Zárate-Carbajal, E. A. Lagarda-Clark, S. Mikhaylin, and A. Duarte-Sierra, “Untargeted metabolomic analysis of strawberries exposed to pulsed electric fields and cold plasma before postharvest storage,” Future Foods, vol. 9, p. 100364, Jun. 2024, doi: 10.1016/j.fufo.2024.100364.

[21] M. Giannoglou et al., “Effect of cold atmospheric plasma and pulsed electromagnetic fields on strawberry quality and shelf-life,” Innovative Food Science & Emerging Technologies, vol. 68, p. 102631, Mar. 2021, doi: 10.1016/j.ifset.2021.102631.

[22] S. Rana, D. Mehta, V. Bansal, U. S. Shivhare, and S. K. Yadav, “Atmospheric cold plasma (ACP) treatment improved in-package shelf-life of strawberry fruit,” J Food Sci Technol, vol. 57, no. 1, pp. 102–112, Jan. 2020, doi: 10.1007/s13197-019-04035-7.

[23] D. Ziuzina et al., “Investigation of a large gap cold plasma reactor for continuous in-package decontamination of fresh strawberries and spinach,” Innovative Food Science & Emerging Technologies, vol. 59, p. 102229, Jan. 2020, doi: 10.1016/j.ifset.2019.102229.

[24] M. Giannoglou et al., “Effect of cold atmospheric plasma and pulsed electromagnetic fields on strawberry quality and shelf-life,” Innovative Food Science & Emerging Technologies, vol. 68, p. 102631, Mar. 2021, doi: 10.1016/j.ifset.2021.102631.

[25] M. Li, X. Li, C. Han, N. Ji, P. Jin, and Y. Zheng, “Physiological and Metabolomic Analysis of Cold Plasma Treated Fresh-Cut Strawberries,” J Agric Food Chem, vol. 67, no. 14, pp. 4043–4053, Apr. 2019, doi: 10.1021/acs.jafc.9b00656.

[26] X. Yang, C. Zhang, Q. Li, and J.-H. Cheng, “Physicochemical Properties of Plasma-Activated Water and Its Control Effects on the Quality of Strawberries,” Molecules, vol. 28, no. 6, p. 2677, Mar. 2023, doi: 10.3390/molecules28062677.

[27] A. Zárate-Carbajal, E. A. Lagarda-Clark, S. Mikhaylin, and A. Duarte-Sierra, “Untargeted metabolomic analysis of strawberries exposed to pulsed electric fields and cold plasma before postharvest storage,” Future Foods, vol. 9, p. 100364, Jun. 2024, doi: 10.1016/j.fufo.2024.100364.

[28] Z. A. Belay, N. E. Nyamende, and O. J. Caleb, “Impact of cold plasma-mediated treatment on coated and packaged ‘Monterey’ strawberries during cold storage,” South African Journal of Plant and Soil, vol. 39, no. 4, pp. 302–307, Oct. 2022, doi: 10.1080/02571862.2022.2104946.

[29] H. Xu, C. Liu, and Q. Huang, “Enhance the inactivation of fungi by the sequential use of cold atmospheric plasma and plasma-activated water: Synergistic effect and mechanism study,” Chemical Engineering Journal, vol. 452, p. 139596, Jan. 2023, doi: 10.1016/j.cej.2022.139596.

[30] S. S. Siddique, G. E. St. J. Hardy, and K. L. Bayliss, “Cold plasma: a potential new method to manage postharvest diseases caused by fungal plant pathogens,” Plant Pathol, vol. 67, no. 5, pp. 1011–1021, Jun. 2018, doi: 10.1111/ppa.12825.

[31] Z. Yang, Q. Wu, F. Jiang, D. Zheng, D. Wu, and K. Chen, “Indirect treatment of plasma-processed air to decrease decay and microbiota of strawberry fruit caused by mechanical damage,” Food Chem, vol. 408, p. 135225, May 2023, doi: 10.1016/j.foodchem.2022.135225.

[32] P. Brun et al., “Antibacterial efficacy and mechanisms of action of low power atmospheric pressure cold plasma: membrane permeability, biofilm penetration and antimicrobial sensitization,” J Appl Microbiol, vol. 125, no. 2, pp. 398–408, Aug. 2018, doi: 10.1111/jam.13780.

[33] X. Liao, D. Liu, S. Chen, X. Ye, and T. Ding, “Degradation of antibiotic resistance contaminants in wastewater by atmospheric cold plasma: kinetics and mechanisms,” Environ Technol, vol. 42, no. 1, pp. 58–71, Jan. 2021, doi: 10.1080/09593330.2019.1620866.

[34] H. Feng et al., “The Interaction of a Direct-Current Cold Atmospheric-Pressure Air Plasma With Bacteria,” IEEE Transactions on Plasma Science, vol. 37, no. 1, pp. 121–127, Jan. 2009, doi: 10.1109/TPS.2008.2008438.

[35] C. Lan et al., “Disinfection of viruses with cold atmospheric-pressure plasmas: Sources, mechanisms, and efficacy,” Plasma Processes and Polymers, vol. 21, no. 3, Mar. 2024, doi: 10.1002/ppap.202300183.

[36] X. Liao, D. Liu, S. Chen, X. Ye, and T. Ding, “Degradation of antibiotic resistance contaminants in wastewater by atmospheric cold plasma: kinetics and mechanisms,” Environ Technol, vol. 42, no. 1, pp. 58–71, Jan. 2021, doi: 10.1080/09593330.2019.1620866.

[37] I. NIEDŹWIEDŹ, A. WAŚKO, J. PAWŁAT, and M. POLAK-BERECKA, “The State of Research on Antimicrobial Activity of Cold Plasma,” Pol J Microbiol, vol. 68, no. 2, pp. 153–164, Jan. 2019, doi: 10.33073/pjm-2019-028.

[38] C. Otto, S. Zahn, F. Rost, P. Zahn, D. Jaros, and H. Rohm, “Physical Methods for Cleaning and Disinfection of Surfaces,” Food Engineering Reviews, vol. 3, no. 3–4, pp. 171–188, Dec. 2011, doi: 10.1007/s12393-011-9038-4.

[39] P. Brun et al., “Disinfection of Ocular Cells and Tissues by Atmospheric-Pressure Cold Plasma,” PLoS One, vol. 7, no. 3, p. e33245, Mar. 2012, doi: 10.1371/journal.pone.0033245.

[40] N. N. Misra et al., “Cold Plasma in Modified Atmospheres for Post-harvest Treatment of Strawberries,” Food Bioproc Tech, vol. 7, no. 10, pp. 3045–3054, Oct. 2014, doi: 10.1007/s11947-014-1356-0.

[41] S. Rana, D. Mehta, V. Bansal, U. S. Shivhare, and S. K. Yadav, “Atmospheric cold plasma (ACP) treatment improved in-package shelf-life of strawberry fruit,” J Food Sci Technol, vol. 57, no. 1, pp. 102–112, Jan. 2020, doi: 10.1007/s13197-019-04035-7.

[42] S. Rana, D. Mehta, V. Bansal, U. S. Shivhare, and S. K. Yadav, “Atmospheric cold plasma (ACP) treatment improved in-package shelf-life of strawberry fruit,” J Food Sci Technol, vol. 57, no. 1, pp. 102–112, Jan. 2020, doi: 10.1007/s13197-019-04035-7.

[43] X. Yepez, A. E. Illera, H. Baykara, and K. Keener, “Recent Advances and Potential Applications of Atmospheric Pressure Cold Plasma Technology for Sustainable Food Processing,” Foods, vol. 11, no. 13, p. 1833, Jun. 2022, doi: 10.3390/foods11131833.

[44] P. J. Cullen et al., “Translation of plasma technology from the lab to the food industry,” Plasma Processes and Polymers, vol. 15, no. 2, Feb. 2018, doi: 10.1002/ppap.201700085.

[45] N. N. Misra et al., “Cold Plasma in Modified Atmospheres for Post-harvest Treatment of Strawberries,” Food Bioproc Tech, vol. 7, no. 10, pp. 3045–3054, Oct. 2014, doi: 10.1007/s11947-014-1356-0.

[46] P. J. Cullen et al., “Translation of plasma technology from the lab to the food industry,” Plasma Processes and Polymers, vol. 15, no. 2, Feb. 2018, doi: 10.1002/ppap.201700085.

[47] J. S. Wilson and T. Otsuki, “To spray or not to spray: pesticides, banana exports, and food safety,” Food Policy, vol. 29, no. 2, pp. 131–146, Apr. 2004, doi: 10.1016/j.foodpol.2004.02.003.

[48] G. R. Warne et al., “Radiofrequency cold plasma – A novel tool for flavour modification in fresh and freeze-dried strawberries,” Innovative Food Science & Emerging Technologies, vol. 90, p. 103497, Dec. 2023, doi: 10.1016/j.ifset.2023.103497.

[49] S. Zargarchi et al., "Exploring the impact of cold plasma treatment on the antioxidant capacity, ascorbic acid, phenolic profile, and bioaccessibility of fruits and fruit juices," Food Front, vol. 5, no. 3, pp. 1108–1125, May 2024, doi: 10.1002/fft2.372.

[50] R. Priyadarshi, A. Jayakumar, C. K. de Souza, J. Rhim, and J. T. Kim, "Advances in strawberry postharvest preservation and packaging: A comprehensive review," Compr Rev Food Sci Food Saf, vol. 23, no. 4, Jul. 2024, doi: 10.1111/1541-4337.13417.

[51] M. Domonkos, P. Tichá, J. Trejbal, and P. Demo, "Applications of Cold Atmospheric Pressure Plasma Technology in Medicine, Agriculture and Food Industry," Applied Sciences, vol. 11, no. 11, p. 4809, May 2021, doi: 10.3390/app11114809.

[52] M. Gavahian, "Opinion on the prospects of emerging food processing technologies to achieve sustainability in the industry by reduced energy consumption, waste reduction and valorisation, and improved food nutrition," Int J Food Sci Technol, vol. 59, no. 11, pp. 8135–8140, Oct. 2024, doi: 10.1111/ijfs.17525.

[53] B. A. Niemira, "Cold Plasma Decontamination of Foods," Annu Rev Food Sci Technol, vol. 3, no. 1, pp. 125–142, Apr. 2012, doi: 10.1146/annurev-food-022811-101132.

[54] L. Mohammadi, A. Ramezanian, F. Tanaka, and F. Tanaka, "Impact of Aloe vera gel coating enriched with basil (Ocimum basilicum L.) essential oil on postharvest quality of strawberry fruit," Journal of Food Measurement and Characterization, vol. 15, no. 1, pp. 353–362, Feb. 2021, doi: 10.1007/s11694-020-00634-7.

[55] R. Thirumdas, C. Sarangapani, and U. S. Annapure, "Cold Plasma: A novel Non-Thermal Technology for Food Processing," Food Biophys, vol. 10, no. 1, pp. 1–11, Mar. 2015, doi: 10.1007/s11483-014-9382-z.

[56] M. Bayati, M. N. Lund, B. K. Tiwari, and M. M. Poojary, "Chemical and physical changes induced by cold plasma treatment of foods: A critical review," Compr Rev Food Sci Food Saf, vol. 23, no. 4, Jul. 2024, doi: 10.1111/1541-4337.13376.

[57] C. J. Hernández-Torres et al., "Recent trends and technological development in plasma as an emerging and promising technology for food biosystems," Saudi J Biol Sci, vol. 29, no. 4, pp. 1957–1980, Apr. 2022, doi: 10.1016/j.sjbs.2021.12.023.

AUTHORS

Apoorva Mishra ,MSc (Horticulture) from Baba Saheb Agriculture University, Lucknow, and pursuing a PhD (Fruit Science) from Shri Ramswaroop Memorial University, Lucknow.

Dr Pranav Kumar Mishra, Assistant Professor, Horticulture IAST, Shri Ramswaroop Memorial University, Lucknow, Uttar Pradesh

Dr. Balvir Singh, Deputy Director, Research IAST, Shri Ramswaroop Memorial University, Lucknow, Uttar Pradesh

Dr. Riyaz Ahmad, Assistant Professor, Agronomy, IAST, Shri Ramswaroop Memorial University, Lucknow, Uttar Pradesh