

COLD PLASMA PROCESSING OF LIQUID FOODS: MECHANISMS, APPLICATIONS, AND FUTURE PERSPECTIVES

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ABSTRACT

Cold plasma (CP) is an emerging non-thermal technology that has gained attention for the preservation of liquid foods because of its ability to inactivate microorganisms while operating at relatively low temperatures. This review summarizes the principles, plasma systems, applications, and quality effects of CP treatment in liquid foods, with particular emphasis on fruit and vegetable juices, coconut water, and neera. The generation of reactive oxygen and nitrogen species during plasma treatment contributes to microbial inactivation through damage to cell membranes and intracellular components. Reported studies demonstrate substantial microbial reductions, including reductions of less than 5 log CFU/mL in selected fruit juices, together with inactivation of spoilage enzymes such as polyphenol oxidase, peroxidase, and pectin methylesterase. CP treatment can maintain several physicochemical and nutritional attributes under suitable conditions, although its effects on phenolic compounds, vitamins, pigments, proteins, sugars, colour, antioxidant activity, and sensory properties depend on plasma type, working gas, treatment intensity, and food composition. Applications in neera remain comparatively limited, although available studies indicate microbial reduction with relatively small changes in colour and total soluble solids. The review also discusses challenges related to plasma–food interactions, treatment uniformity, energy consumption, reactor design, gas selection, and storage stability. Future research should focus on matrix-specific process optimization, continuous-flow systems, energy-efficient treatment, and combinations with suitable packaging and refrigerated storage to improve the consistency and applicability of CP for liquid-food preservation.

KEYWORDS: Cold plasma, Liquid foods, Microbial inactivation, Fruit juices, Traditional beverages

1. INTRODUCTION

Fruit juices and traditional beverages are widely consumed because of their nutritional and functional properties. These food products can provide carbohydrates, proteins, lipids, vitamins, minerals, phenolic compounds, and other bioactive components, depending on their source and composition (Butu and Rodino, 2019). However, the high moisture content and availability of nutrients make liquid foods highly susceptible to microbial growth and quality deterioration. Bacteria, yeasts, and moulds can cause spoilage and fermentation, while enzymatic and oxidative reactions can result in undesirable changes in colour, flavour, aroma, nutritional quality, and other physicochemical characteristics (Mafe et al., 2024). Therefore, maintaining the safety, quality, and nutritional value of liquid foods during processing and storage is an important consideration in the food industry.

Various conventional methods are used to extend the shelf life of liquid foods. Among them, thermal treatments such as pasteurization and sterilization are widely used for their effectiveness in reducing microorganisms and inactivating spoilage enzymes (Maurya, 2025). Additionally, refrigeration is used to slow down microbial growth and biochemical reactions, while chemical preservatives may be applied to selected products to control microbial deterioration (Alhassan et al., 2025). Other approaches, such as fermentation, concentration, and filtration, are also used depending on the characteristics of the food product. Although these methods can effectively improve product stability, their application may be associated with certain limitations (Siddiqui et al., 2023).

Heat treatment can cause undesirable changes in heat-sensitive nutrients and bioactive compounds and may affect colour, flavour, aroma, and other quality attributes. Prolonged heating can also alter proteins, vitamins, pigments, and other food components (Ağçam et al., 2018). Refrigeration can reduce the rate of deterioration but requires continuous temperature control during storage and distribution (Ovca et al., 2021). The use of chemical preservatives may also be restricted by consumer preference (Guzik et al., 2022). To avoid these limitations, non-thermal preservation technologies have emerged as alternatives for microbial control while minimizing undesirable changes in food quality. Technologies such as high-pressure processing, pulsed electric fields,

ultraviolet treatment, ultrasound, membrane filtration, and cold plasma are increasingly studied for liquid food preservation. Depending on the technology and processing conditions, these approaches use physical mechanisms other than conventional heating to control microorganisms and retain nutrients (Jadhav et al., 2021).

Among these, cold plasma has emerged as an important technology for preserving liquid foods. It has been studied for microbial reduction and shelf-life extension, along with its effects on physicochemical properties, nutritional components, enzyme activity, antioxidant activity, and sensory quality (Ma et al., 2026). Such studies have increased interest in cold plasma as an alternative preservation method for liquid foods. Despite the growing research on cold plasma, information on its application to different liquid-food products remains scattered. This review provides an overview of cold plasma treatment for liquid foods, focusing on microbial inactivation, shelf-life extension, and changes in physicochemical, nutritional, enzymatic, antioxidant, and sensory properties. The review also covers its applications in fruit juices and traditional beverages such as neera, while highlighting current limitations and future research directions.

2. Cold Plasma Technology: Principle and mechanism

Cold plasma is generated when electrical energy is applied to a gas, causing partial ionization of the gas containing electrons, ions, neutral molecules, and reactive species. Cold plasma differs from thermal plasma because the bulk temperature remains relatively low, generally below 40–60°C, making it suitable for heat-sensitive liquid foods (Huang et al., 2026). During plasma generation, interactions between energetic electrons and gas molecules produce reactive oxygen and nitrogen species (RONS). These reactive species interact with the microbial cell membrane, damaging membrane integrity, causing leakage of intracellular materials, and ultimately leading to microbial inactivation (Bayati et al., 2024).

The working gas is an important factor in cold plasma generation because it determines the type and abundance of reactive species produced during treatment. Air, oxygen, nitrogen, argon, and helium are commonly used gases in food sectors (Bezerra et al., 2023). Air is economical, readily available, and can generate both reactive oxygen and nitrogen species. Oxygen-rich plasmas favour reactive oxygen species (ROS) such as ozone (O_3), hydrogen peroxide (H_2O_2), superoxide ($O_2^{\cdot-}$), and hydroxyl radicals ($\cdot OH$), whereas nitrogen promotes the formation of reactive nitrogen species (RNS) such as nitric oxide (NO), nitrite (NO_2^-), and nitrate (NO_3^-) (Kumar et al., 2024). Argon and helium are chemically inert gases that facilitate stable plasma formation and are particularly common in atmospheric-pressure plasma jets. Gas mixtures, such as Ar/ O_2 , He/ O_2 , and Ar/ N_2 , can also be used to modify the reactive-species composition and treatment intensity. The selection of gas therefore influences plasma stability, reactive-species generation, microbial inactivation, and the extent of changes in food quality (Heneral and Avtaeva, 2020).

The efficiency of cold plasma treatment depends on operating parameters such as applied voltage, power, frequency, treatment time, type of working gas, gas-flow rate, electrode distance, and reactor configuration. Food-related factors such as pH, electrical conductivity, viscosity, turbidity, dissolved solids, protein and fat content, and microbial load can also influence treatment efficiency by affecting the generation, transmission, and interaction with reactive species (Feizollahi et al., 2021). Increasing treatment intensity generally improves microbial reduction, but excessive exposure may increase oxidation and undesirable quality changes (K. Zhang et al., 2026). Thus, optimization of processing conditions is essential for achieving effective microbial inactivation with minimum effects on food quality.

3. Types of Cold Plasma Systems

Different cold plasma systems have been developed based on electrode arrangement, discharge mechanism, operating pressure, and method of plasma generation. Common systems used for food preservation include dielectric barrier discharge (DBD), atmospheric-pressure plasma jet (APPJ), corona discharge, gliding arc discharge, and microwave discharge plasma (Ganesan et al., 2021). These systems differ in their energy-transmission mechanisms and plasma characteristics, which influence their suitability for different food applications (Figure 1).

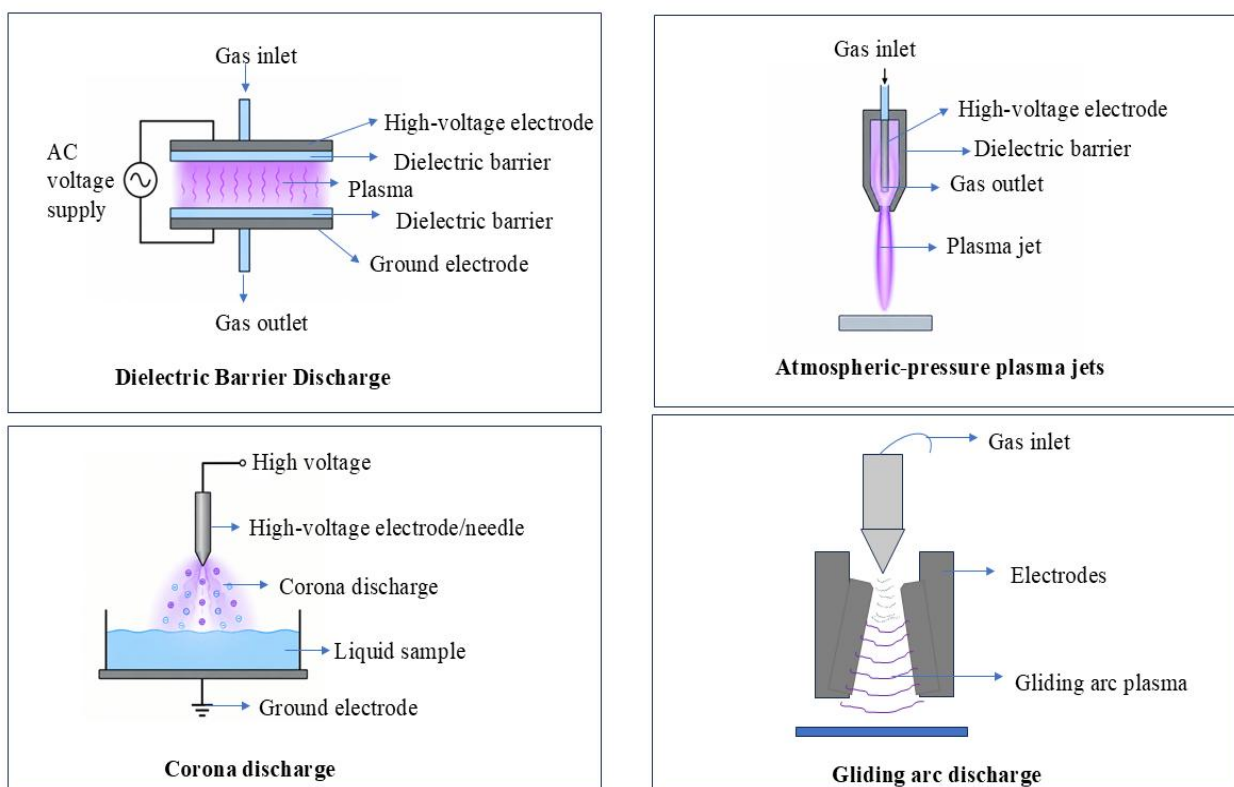
Dielectric barrier discharge (DBD) is one of the most widely studied atmospheric-pressure plasma systems for food preservation. In a DBD reactor, plasma is generated between two electrodes, with at least one electrode covered by an insulating dielectric material such as glass, quartz, or ceramic. When a high-voltage alternating or pulsed electric field is applied, numerous micro discharges are produced within the gap (Palma et al., 2020). Typical systems operate at voltages of approximately 1–100 kV, with treatment times ranging from seconds to several minutes, depending on reactor design and food product. DBD can be configured for direct treatment of liquids or treatment through the gas–liquid interface (Feizollahi et al., 2021). Atmospheric-pressure plasma jets (APPJs) generate plasma using a flowing working gas, such as helium, argon, air, nitrogen, or oxygen. Plasma is produced within a discharge region and extends outward as a plasma plume. Plasma jets provide localized treatment and can operate with relatively low gas temperatures, making them suitable for heat-sensitive foods (Shang et al., 2024). For liquid foods, the plasma plume can be directed toward the liquid surface to promote interaction between reactive species and the product. However, the limited treatment area of individual jets can restrict their use for large-volume processing unless multiple jets or continuous systems are employed (Truong and Ishijima, 2026).

Corona discharge is produced when a strong electric field is established around an electrode with a small radius of curvature, such as a needle or pointed electrode. The high electric field initiates ionization of the surrounding

gas and produces a corona discharge. Depending on electrode geometry and reactor design, voltages of up to 30 kV may be applied (Acar et al., 2024). Corona discharge has been investigated for microbial inactivation and food preservation because of its relatively simple configuration and effective generation of reactive species. However, discharge stability, treatment uniformity, and possible ozone accumulation require consideration during processing (Zhu et al., 2022). Gliding arc discharge is generated between two diverging electrodes. An electric arc initially forms near the narrowest electrode gap and is then extended along the electrodes by the movement of the working gas. The system generally operates at atmospheric pressure and can provide relatively high reactive-species production and gas throughput. Treatment times commonly range from seconds to several minutes, depending on reactor design and operating conditions (Seyedalangi et al., 2025). Gliding arc systems are used for continuous and higher-throughput processing, although the relatively high energy input may increase the treatment temperature and therefore requires appropriate control for heat-sensitive foods (Yu et al., 2025).

Microwave discharge plasma is generated by coupling microwave energy into a working gas rather than using direct electrical contact between electrodes. Common microwave frequencies include 2.45 GHz, which is widely used in laboratory and industrial microwave systems. The microwave electric field transfers energy to free electrons in the gas, producing excitation, ionization, and dissociation and subsequently forming plasma. Argon, helium, nitrogen, oxygen, and air can be used depending on the desired plasma characteristics. Microwave plasma can operate at atmospheric pressure or reduced pressure and can generate high concentrations of reactive species with relatively efficient energy transfer. Their advantages include electrode-free plasma generation, which can reduce electrode erosion and contamination, and the possibility of continuous operation. However, reactor design, microwave power distribution, treatment uniformity, and temperature control are important considerations, particularly for liquid foods. The selection of a plasma system depends on the food type, treatment volume, required microbial reduction, processing time, energy input, and desired quality retention. DBD and plasma jets are frequently used in laboratory-scale food studies, while gliding arc and microwave systems provide opportunities for higher-throughput or continuous processing. Therefore, the characteristics of each plasma configuration should be considered when selecting a system for liquid-food preservation.

Figure 1. Types of cold plasma systems



4. Influence of cold plasma on nutritional attributes of liquid foods

Cold plasma treatment can influence the nutritional, physicochemical, enzymatic, and sensory properties of liquid foods in addition to its antimicrobial effect (Alijanibaei et al., 2025). The extent and direction of these changes depend mainly on treatment intensity, exposure time, plasma type, working gas, and the characteristics of the food (Zhang et al., 2022). Appropriate treatment conditions can help maintain the quality of liquid foods, whereas excessive exposure to reactive species may promote oxidation and degradation of sensitive components.

Phenolic compounds are important quality attributes of fruit juices and other beverages. Cold plasma treatment may cause partial oxidation or transformation of phenolic compounds through reactions with reactive oxygen and nitrogen species. However, the disruption of plant tissues and release of bound phenolics under suitable treatment

conditions may also increase the measured phenolic content and antioxidant activity (Cebeci and Kamiloglu, 2026). Under mild conditions, substantial retention of these compounds can generally be achieved, whereas prolonged treatment may accelerate oxidation.

Sugars and organic acids can also be affected during plasma treatment. Major sugars such as glucose, fructose, and sucrose are generally relatively stable under mild conditions, while prolonged exposure to reactive species may promote oxidation or degradation (Farooq et al., 2023). Organic acids contribute to the characteristic taste and acidity of beverages, and changes in their concentration may influence pH and flavour. In most liquid-food applications, moderate plasma treatment produces limited changes in total soluble solids and major organic acids, although stronger treatments may result in measurable changes (Sorathiya et al., 2025).

Reactive species generated during plasma treatment can oxidize amino acid residues and modify protein structure, which may influence solubility, aggregation, surface properties, and functional characteristics. Moderate treatment conditions may produce limited protein changes, whereas excessive treatment can promote protein oxidation and aggregation (Rout et al., 2025). Plasma treatment can also affect enzymes responsible for quality deterioration. Enzymes such as PPO and POD may be partially or substantially inactivated through oxidative modification (Chakraborty et al., 2025).

Vitamins and other bioactive compounds may show different levels of stability during plasma treatment. Water-soluble vitamins, particularly ascorbic acid, are susceptible to oxidation, while the retention of other vitamins depends on their chemical structure and treatment intensity (Zargarchi et al., 2024). Pigments such as carotenoids and anthocyanins may also undergo oxidation or structural transformation. Therefore, minimizing unnecessary exposure to reactive species is important when the nutritional value of the product is a major consideration (Cebeci and Kamiloglu, 2026).

Cold plasma can additionally affect colour, flavour, aroma, turbidity, and viscosity. Colour changes may result from oxidation or transformation of pigments and phenolic compounds, while flavour and aroma may be influenced by oxidation products and changes in volatile compounds. Under optimized conditions, these changes can be limited, whereas excessive treatment may produce noticeable sensory differences (Zhang et al., 2022).

Plasma-generated reactive species may promote the formation or release of certain bioactive compounds and improve antioxidant-related responses under appropriate conditions. Conversely, excessive oxidation may lead to undesirable compounds and off-flavour formation. Therefore, the objective of plasma processing is not simply to maximize treatment intensity but to achieve an appropriate balance between microbial inactivation and retention of nutritional and sensory quality. Overall, the reported effects demonstrate that cold plasma can be used to preserve the quality of liquid foods when processing conditions are carefully controlled.

5. Application of cold plasma treatment in liquid foods

5.1 Fruit and Vegetable Juices

Cold plasma has been applied to several fruit and vegetable juices to reduce microbial contamination while maintaining their nutritional and physicochemical quality (Table 1). In orange juice, high-voltage atmospheric cold plasma achieved more than a 5-log reduction of *Salmonella enterica* after 30 s of treatment. Longer treatment also reduced pectin methylesterase activity by 74–82%, while pH and total soluble solids remained relatively unchanged (Xu et al., 2017). However, vitamin C decreased by approximately 22% after direct plasma treatment for 120 s, which was lower than the reduction observed during thermal pasteurization.

In siriguela juice, nitrogen glow-discharge plasma increased the total phenolic content by up to 58% and improved DPPH antioxidant activity from 492.19 ± 8.67 to 817.43 ± 13.00 μM Trolox/mL under the tested conditions. Lycopene content increased by approximately 30–50%, while polyphenol oxidase activity decreased to $78.54 \pm 0.63\%$ of the untreated value (Paixão et al., 2019). In camu-camu juice, dielectric barrier discharge plasma influenced ascorbic acid and anthocyanin contents. Ascorbic acid increased with plasma excitation frequency, whereas anthocyanin content decreased at higher frequencies. The colour difference remained relatively low, with ΔE values ranging from 0.8 to 1.1 (De Castro et al., 2020).

Cold atmospheric pressure plasma has also been used to process beetroot juice. Continuous-flow plasma systems altered phenolic compounds, while carbohydrates remained essentially unchanged and betalains were only slightly affected. Some increases in mineral concentration were associated with water evaporation during treatment rather than actual mineral enrichment (Dzimitrowicz et al., 2021).

In white grape juice, treatment at 80 kV for 4 min resulted in a 7.4 log CFU/mL reduction of *Saccharomyces cerevisiae*, while up to a 7.2 log CFU/mL reduction of *Bacillus* spp. was reported in blueberry juice following plasma-jet treatment (Pankaj and Keener, 2017). In apple juice, cold plasma treatment achieved approximately a 4.3 log CFU/mL reduction of *Escherichia coli* O157 under optimized conditions, whereas a 4.7 log CFU/mL reduction of *Salmonella enterica* was reported in orange juice (Ozen and Singh, 2020). In orange juice, dielectric barrier discharge (DBD) treatment also achieved more than 5-log reductions of *Staphylococcus aureus*, *E. coli*, and *Candida albicans*, demonstrating the strong antimicrobial potential of plasma treatment (Waghmare, 2021).

The nutritional response to cold plasma varies considerably with the plasma conditions and juice matrix. In cashew apple juice, plasma treatment increased ascorbic acid by 10.4–10.8%, while the total phenolic content increased by approximately 101–108% under selected treatment conditions (Rodríguez et al., 2017). In pomegranate juice, plasma-jet treatment resulted in a 21–35% increase in anthocyanin content, indicating that controlled plasma exposure can enhance the release or availability of certain bioactive compounds (Zargarchi et al., 2024). Similarly,

atmospheric plasma-jet treatment increased total phenolic content by 9.52% in orange juice, 14.81% in tomato juice, and 14.43% in apple juice under the reported processing conditions (Waghmare, 2021). These studies indicate that plasma treatment can support microbial control, enzyme inactivation, and the retention or improvement of selected bioactive compounds in fruit and vegetable juices. However, treatment intensity must be controlled because excessive exposure may affect vitamin C, pigments, colour, and other quality attributes.

5.2 Neera and Other Liquid Foods

Cold plasma has also been investigated for coconut water, coconut neera, and other liquid beverages (Table 1). In coconut water, the colour difference remained low immediately after treatment, with ΔE values of 0.14, 0.18 and 0.29 after 3, 6 and 12 s, respectively. Plasma treatment also reduced polyphenol oxidase and peroxidase activities, while the 12 s treatment produced FRAP, DPPH, and ABTS values of 15.77 Fe^{2+}/g , 37.15%, and 39.51%, respectively (Zeng et al., 2025).

In coconut neera, plasma bubbling was studied using different gas-flow rates, treatment times, and applied voltages. Hydroxyl radicals were detected during treatment, confirming the formation of reactive species. The process reduced the microbial population by approximately 80% and increased the pH by about 1.04 units. Only negligible changes were observed in colour and TSS. The nutritional composition was largely maintained, although vitamin C decreased to approximately 4.7 mg/100 mL after treatment (Aparajhitha and Mahendran, 2019). Rodrigues and Fernandes (2023) identified 24 volatile compounds after plasma treatment and reported changes in terpenoid and aldehyde compounds associated with orange juice aroma. Overall, cold plasma applications in neera and other liquid foods mainly involve microbial reduction, enzyme control, preservation of physicochemical quality, modification of antioxidant properties, and changes in aroma-related compounds. The extent of these effects depends on the plasma system, gas type, treatment voltage, exposure time, flow rate, and composition of the liquid food.

Table 1. Applications of cold plasma technology in juices and traditional beverages

Food/beverage	Type of cold plasma	Operating parameters	Major effects observed	Reference
Orange juice	High-voltage atmospheric cold plasma (HVACP)	Voltage: 90 kV Frequency: 60 Hz Time: 120 s	• <i>S. enterica</i> reduction of up to 4.7 log CFU/mL after storage • pH and °Brix remained relatively unchanged • PME activity decreased by 82% • Vitamin C decreased by about 22%	(Xu et al., 2017)
Tomato juice	Atmospheric plasma jet (AJP)	Power: 650 W Flow rate: 50 L/min Time: 120 s	• <i>E. coli</i> reduced by up to 1.6 log CFU/mL • Total phenolic content increased by approximately 9.52%	(Dasan and Boyaci, 2018)
Orange juice	DBD plasma	Excitation frequency: 50–600 Hz	• Modified volatile profile • Increased terpenoid and aldehyde compounds associated with fresh-like aroma and controlled off-flavour formation	(Rodrigues and Fernandes, 2023)
Siriguela juice	Low-pressure glow discharge plasma	Flow rate: 10–30 mL/min Time: 5–15 min Power: 80 W Frequency: 50 kHz	• Vitamin C and colour were maintained • TPC increased by up to 58% • PPO activity decreased by about 20%	(Paixão et al., 2019)
Camu-camu juice	DBD plasma	Excitation frequencies: 200, 420, 583, 698, and 960 Hz	• Ascorbic acid increased with increasing frequency • Anthocyanins decreased at higher frequencies • PPO and POD activities decreased	(De Castro et al., 2020)

			• Colour difference remained low ($\Delta E \approx 0.7\text{--}1.1$)	
White grape juice	High-voltage atmospheric cold plasma	Voltage: 80 kV Frequency: 60 Hz Time: 4 min	• <i>S. cerevisiae</i> reduction of approximately 7.4 log CFU/mL	(Pankaj et al., 2017)
Blueberry juice	Atmospheric jet plasma	Voltage: 11 kV Frequency: 1000 Hz Flow rate: 1 L/min Time: 6 min	• <i>Bacillus</i> spp. reduction of approximately 7.2 log CFU/mL • Colour was relatively well preserved	(Hou et al., 2019)
Sour cherry nectar	Atmospheric jet plasma	Power: 650 W Flow rate: 50 L/min Time: 120 s	• <i>E. coli</i> reduction of approximately 3.3 log CFU/mL • TPC increased by approximately 14.47%	(Waghmare, 2021)
Fresh tomato juice	Gliding discharge plasma	Power: 40 W Voltage: 3.8 kV Frequency: 50 Hz Flow rate: 440 L/min Time: 5 min	• 5 log CFU/mL reduction in total aerobic mesophilic bacteria • 4.9 log reduction in yeasts • 3.5 log reduction in moulds	(Starek et al., 2019)
Cashew apple juice	Indirect cold plasma	Flow rate: 10, 30, and 50 mL/min Time: 5–15 min	• Ascorbic acid increased by 10.4–10.8% • TPC increased by approximately 101–108%	(Rodríguez et al., 2017)
Pomegranate juice	Plasma jet	Voltage: 2.5kV Time: 3,5, and 7 min	• Anthocyanin content increased by approximately 21–35%, indicating improved release of bioactive compounds	(Zargarchi et al., 2024)
Coconut neera	Atmospheric-pressure cold plasma	Flow rate: 5, 7 and 10 L/h Voltage: 150 and 200 V Time: 5 and 10 min	• Approximately 80% microbial reduction • pH increased by 1.04 units • Negligible changes in colour and TSS • Nutritional profile largely maintained • Slight vitamin C reduction	(Aparajhitha and Mahendran, 2019)
Coconut water	Atmospheric jet plasma	Time: 3, 6, and 12 s	• Low colour change (ΔE 0.14–0.29) • PPO and POD activities decreased • Microbial growth during refrigerated storage was inhibited • Antioxidant responses were affected by treatment duration	(Zeng et al., 2025)

6. Challenges and Future Perspectives

Although cold plasma has shown promising results in liquid-food preservation, several factors need to be considered for its effective application. Plasma–food interactions are influenced by food composition, viscosity, conductivity, pH, and surface characteristics. Reactive oxygen and nitrogen species generated during treatment can interact with microorganisms as well as proteins, lipids, pigments, vitamins, and phenolic compounds. Therefore, the same plasma conditions may produce different effects in different liquid-food matrices. Treatment conditions should be optimized according to the characteristics of each food to achieve microbial inactivation while maintaining nutritional and sensory quality. Treatment uniformity is another important challenge, particularly for larger volumes of liquid foods. Direct treatment may result in uneven exposure when plasma interacts mainly with the liquid surface. Continuous-flow systems can improve contact between reactive species and the liquid, although their performance depends on flow conditions and reactor design. Suitable reactor configurations are therefore needed to achieve consistent treatment.

Energy consumption should also be considered, as higher voltage, longer treatment time, and greater gas flow may improve microbial inactivation but increase energy use and cause undesirable quality changes. Optimization should therefore consider microbial reduction, energy consumption, treatment time, and quality retention, with parameters such as voltage, frequency, treatment time, gas type, flow rate, and electrode distance adjusted according to the food matrix. Plasma gas selection is also important because different gases generate different reactive species. Air and oxygen-based plasmas mainly promote reactive oxygen species formation, whereas nitrogen-containing systems generate reactive nitrogen species. Helium and argon can provide stable plasma discharges and influence reactive species formation and transfer. Gas selection should therefore consider the required microbial inactivation and the sensitivity of food components to oxidation. Packaging and storage conditions also require attention because surviving microorganisms may grow during storage. Appropriate packaging and refrigerated storage may help maintain the quality achieved after treatment, although their effects should be evaluated for individual liquid foods.

Neera and other traditional beverages require further investigation because fewer studies have examined their response to cold plasma compared with fruit juices. Their high sugar content, near-neutral pH and rapid microbial deterioration make treatment optimization particularly important. Future studies should evaluate microbial changes, fermentation-related reactions, enzyme activity, sugars, phenolic compounds, vitamins, colour, flavour and sensory quality during storage. Combining cold plasma with refrigeration, suitable packaging or other non-thermal treatments may provide effective microbial control at lower treatment intensities. Overall, optimization of plasma–liquid interactions, reactor design, treatment uniformity, energy efficiency and storage conditions is essential for developing reliable cold plasma processes for different liquid foods.

7. CONCLUSION

Cold plasma is an emerging non-thermal technology with considerable potential for preserving liquid foods such as fruit and vegetable juices, coconut water, neera, and other beverages. Studies have demonstrated its ability to reduce microbial populations, inactivate spoilage enzymes, and maintain several important physicochemical and nutritional attributes while operating at relatively low temperatures. However, the effects of plasma treatment depend strongly on the plasma system, gas type, treatment intensity, and characteristics of the food matrix, and excessive treatment may affect sensitive components such as vitamins, pigments, phenolic compounds, and flavour compounds. In particular, limited studies on neera and other traditional liquid beverages indicate the need for further research on microbial control, quality retention, and storage stability. Future work should focus on optimizing treatment conditions, improving reactor design and treatment uniformity, reducing energy requirements, and evaluating suitable combinations with packaging and refrigerated storage. Overall, systematic optimization of plasma processing according to individual liquid-food characteristics is essential for developing effective and consistent preservation processes.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Tamil Nadu Agricultural University for providing the necessary infrastructure and institutional support. The authors also express gratitude to the Indian Council of Agricultural Research-All India Coordinated Research Project on Post-Harvest Engineering and Technology for their valuable guidance.

Author contributions

M. Kirithika: Conceptualization, Methodology, Analysis, Writing – original draft, Validation. **G. Amuthaselvi:** Conceptualization, Formal analysis, Validation, Writing – review & editing. **M. Balakrishnan:** Formal analysis, Investigation. **M. Anand:** Formal analysis, Investigation. **M. R. Manikantan:** Formal analysis, Investigation.

Funding

No financial support was received for this study.

Data availability

No new data were generated or analysed in this study. Data sharing does not apply to this article.

Conflict of interest

The authors declare no conflicts of interest

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