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Article

Cold Atmospheric Plasma for Food Safety and Preservation: Mechanisms, Applications, and Challenges

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Abstract: The largest issues facing the modern food industry are food security and protection, as microbiological contamination, low nutritional quality, and chemical deficiencies directly endanger both public health and financial stability. Energy expenditure, alterations in sensory quality, and customer issues with chemical residues are all consequences of traditional preservation techniques including chilling, pasteurization, and chemical additions. Cold atmospheric plasma (CAP) has proven to be a promising non-citrus, environmentally friendly technology that can effectively neutralize a wide range of microorganisms and at the same time maintain nutrition and sensory quality of food, maintains food nutrition and sensory quality.In addition to microbial inactivity and biochemical alterations, such as rollers in the form of reactive oxygen and nitrogen species (RON), this review offers a thorough observation of plasma file interactions. We also talk about the influence of CAP on food quality attributes, the difficulties in widespread adoption, and new developments in CAP applications in other food areas. Lastly, the future strategy is shown to integrate with existing food safety technologies, industry acceptance, and regulatory considerations.

Keywords: Cold Atmospheric Plasma (CAP), Food Preservation, Non-Thermal Processing, Microbial Inactivation, Food Safety, Nutritional Quality, Shelf Life Extension, Plasma–food Interactions

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1. Introduction

Ensuring food security and expanding durability is one of the most important preferences in the global food industry. According to the World Health Organization (WHO), food -borne diseases affect around 600 million people and cause over 420,000 deaths worldwide, representing a major public health and financial challenge [1]. Traditional protective methods such as cooling, cold, pasteurization, radiation and use of chemical preservatives have been widely used to address microbial pollution and malfunction[2]. However, these methods are often associated with significant deficiencies: cooling and cold require high energy entrance; Thermal treatment can reduce heat - sensitive vitamins and proteins and adversely affect texture and taste; While chemical preservation is quickly investigated due to concerns about poisoning, allergenity, antimicrobial resistance and consumer acceptance [3.4]. In response to these challenges, innovative non-theme food processing technologies have emerged as a safe and more durable alternative. Techniques such as high pressure treatment (HPP), vibrant electric fields (PEF) and ultraviolet (UV) radiation have been detected with different degrees of success[5, Among them, cold atmospheric plasma (cap) has recently attracted increasing attention due to its remarkable antimicrobial activity with minimal effects on nutrition and sensory properties of food [6,7]. Cap is a partially ionized gas that is almost produced at room temperature and atmospheric pressure, with reactive oxygen and nitrogen species (RON), charged particles, UV photons and electric fields. These active ingredients can interact continuously to neutralize a wide range of microorganisms including bacteria, fungi and viruses without the need for high temperatures [8,9]. In addition to microbial inactivity, CAP has been investigated to affect the characteristics of food quality. Studies have shown that cap treatment can effectively increase fruits, vegetables, dairy products and durability of fruits, vegetables, dairy products and meat, and retains desirable properties such as color, taste and nutritional composition [10]. In addition, cap can be used in several ways: directly on food surfaces, indirectly through plasma-active gases or liquids, or as a tool to strong food contact materials and packaging and packaging and packaging[6,11]. This versatility emphasizes the promise as a multifunctional conservation technology. Due to these benefits, the large industrial adoption of cap is limited, mainly due to unresolved challenges related to process standardization, equipment costs, possible formation of toxic by -products and intervals in regulatory approval [8.4]. In addition, consumer beliefs and acceptance of plasma -information food represent an additional obstacle, which requires careful assessment in future studies. It aims to provide a comprehensive and updated observation of cold atmospheric plasma applications in food security and protection. This will emphasize the basic mechanism of plasma -FOCAL interactions, focusing on microbial inactivity paths and biochemical modifications. This will then summarize newer advances in CAP applications in different food areas, followed by a significant analysis of its impact on sensory and nutritional quality. Finally, this review will address the current boundaries and future approaches to CAP technology, highlighting the industrial challenges, security problems and regulatory structure required for its extensive implementation in the food industry.

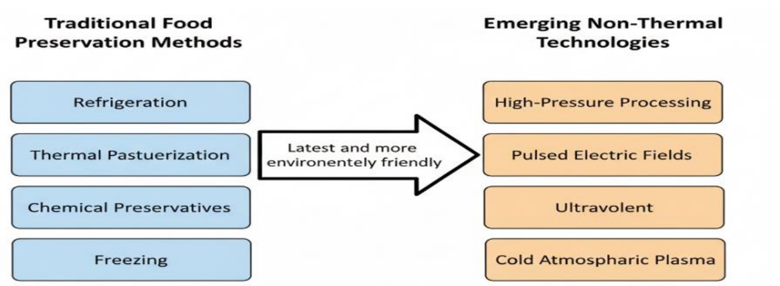

Figure 1. Comparison between traditional food preservation methods (refrigeration, thermal pasteurization, and chemical preservatives) and emerging non-thermal technologies (HPP, PEF, UV, and CAP). Cold atmospheric plasma (CAP) stands out as a promising environmentally friendly alternative.

1. Mechanisms of Plasma Interaction with Food Cold atmospheric plasma (CAP)

Exerts its effects on food systems primarily through a complex interplay of reactive species, physical factors, and surface interactions. Understanding these mechanisms is essential for explaining microbial inactivation, preservation efficacy, and the impact on food quality.

1.1 Generation of Reactive Species

When a working gas (air, argon, oxygen, nitrogen, or mixtures thereof) is exposed to an electric field, it becomes partially ionized, generating a variety of reactive oxygen species (ROS) such as ozone (O_3), hydroxyl radicals (•OH), superoxide (O_2^-), and singlet oxygen ($^1O_2$), as well as reactive nitrogen species (RNS) such as nitric oxide (NO), nitrogen dioxide (NO_2), and peroxynitrite ($ONOO^-$) [12–14]. These short-lived and long-lived species diffuse to food surfaces, where they interact with microbial cells and organic molecules.

1.2 Microbial Inactivation Pathways

The antimicrobial effect of the cold atmospheric plasma (CAP) occurs from the collective effect of its reactive components, including reactive oxygen and nitrogen species (RON), UV photons and charging particles. When microorganisms come into contact with plasma treatment, they complete many stresses at the same time. One of the primary mechanisms is oxidative stress, where rose and ozone attacks such as hydroxyl radicals begin to start bacterial membrane and intracellular protein, lipid peroxidation and enzyme inactivity. At the same time, RN interacts nitrogen oxides and peroxinitis with nucleic acid and protein, causing DNA string brakes, basic modifications and loss of replication processes.As a result of this disorder, leakage of intracellular components, loss of metabolic balance and finally cell death. In addition, plasma-raped UV radiation contributes to nucleic acid damage by causing pyrimidine impairments and other photochemical models, inhibiting further microbial growth and viability. In mushrooms and yeast, it is also reported that CAP induces apoptosis county reactions, including chromatin mondance and DNA fragmentation. Overall, these mechanisms explain why CAP can neutralize a comprehensive range of microorganisms, including gram-positive and gram-negative bacteria, bacterial spors, fungal pathogens and even food-borne viruses, all without all high temperatures [15–17].

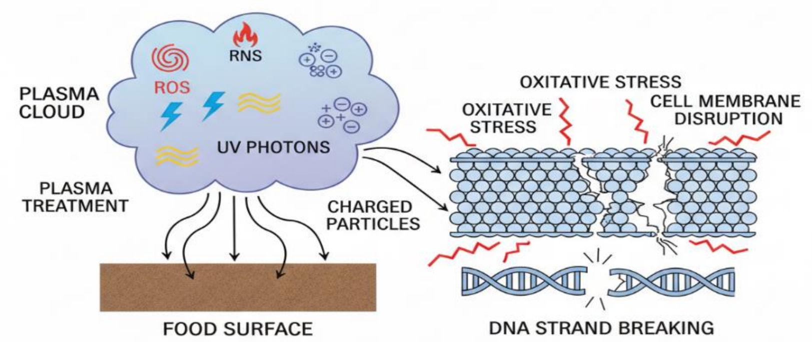

Figure 2. Schematic illustration of the mechanisms of microbial inactivation by cold atmospheric plasma (CAP), including oxidative stress, membrane disruption, and nucleic acid damage induced by reactive oxygen and nitrogen species (RONS), UV photons, and charged particles.

1.3 Effects on Food Constituents

While cold atmospheric plasma (CAP) has shown strong antimicrobial activity, the interaction with food components should also be considered as they directly affect the quality and nutritional value of the treated products. Protein is one of the primary macromolecules affected by plasma exposure. Reactive oxygen and nitrogen species can oxidize specific amino acid side chains, cause structural changes such as disclosures or cross-binding. In some cases, these modifications may increase functional properties, including solubility, emulsion and foamy abilities, which can be beneficial in food processing. However, excessive oxidation protein may compromise digestibility or reduce bioavailability of essential amino acids[18].Lipids are also susceptible to oxidative reactions inspired by plasma-rich particles, especially unsaturated fatty acids. Lipid peroxidation can lead to the formation of secondary products such as aldehydes and ketones, which can change the aroma, taste and the general sensory profile of foods. Nevertheless, when plasma treatment is adapted to low risk and controlled intensity, lipidoxidation is significantly lower than traditional thermal protective methods [19]. Plasma-borne radicals can induce depolarization or partial oxidation of carbohydrate chains, which can improve solutions and digestive power. In some cases, these changes may increase geling, thickness or film -creating properties, and provide possible benefits for food texture and packaging applications. [20].In addition to macronutrients, the stability of micronutrients and antioxidants is an important idea. Vitamins such as ascorbic acid (vitamin C) and tocoferol (vitamin E) are sensitive to oxidative declining. While plasma treatment can cause a moderate reduction in antioxidant materials, many studies indicate that small, carefully controlled treatments retain most vitamins more efficiently than traditional heating processes. In addition, in some cases, plasma exposure may also increase the infections of phenol compounds, which can increase the antioxidant capacity of plant -based foods [21]. Oll, CAP effect on food components depends on the balance between treatment parameters, food composition and microbial inactivity and nutritional quality. Adaptation of these variables is a key challenge to ensure that plasma technologies can achieve food safety goals without compromising the quality of the product.

1.4 Surface and Packaging Interactions

In addition to direct effects on food components, CAP can interact with packaging materials and food contact surfaces. Plasma treatment can sore packaging by neutralizing microorganisms on the surface [22]. In addition, plasma-inspired surface modification can increase hydrophilicity or allow poding of antimicrobial coatings, products can expand durability [23].

2. Applications of Cold Atmospheric Plasma in the Food Industry

The use of cold atmospheric plasma (CAP) in the food sector has expanded greatly in recent years, which has shown its efficiency in improving microbial safety and expanding the durability of a variety of food products. Unlike traditional conservation technologies, CAP offers a non-thermal, chemically-free approach that maintains nutrition and sensory quality of food, and ensures microbial inactivity. The versatility makes it possible to use it directly through raw and processed food as well as indirectly through plasma-active gases or fluids.

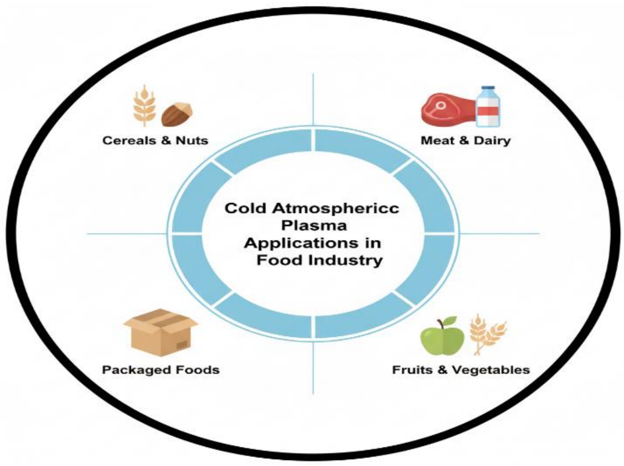

Figure 3. Overview of the main applications of cold atmospheric plasma (CAP) in the food industry, including meat and dairy products, fruits and vegetables, cereals and nuts, and packaged foods.

2.1 Meat and Dairy Products

Meat and dairy products are extremely poor and suffer from microbial pollution during slaughter, processing and storage. Cap treatment has been shown to reduce the population of Eschherichia coli, Salmonella, Listaria monocytozens and Staphylococcus aureus on fresh meat surfaces [24]. For dairy products such as milk, cheese and yogurt, capp pH, protein structure or taste can destroy bacteria and fungi without changing the taste when properly adapted [25]. In addition, CAP has shown the ability to neutralize bacterial spores, which are particularly resistant to traditional passport methods. It is important that sensory studies indicate that plasma meats maintain their specific color and taste profiles better than the thermally treated colleagues [26].

2.2 Fruits and Vegetables

Fresh fruits and vegetables offer unique challenges due to their high moisture content and sensitivity to microbial pollution during harvesting. It has been reported that CAP treatment effectively reduces microbial loads on leafy vegetables, tomatoes, apples, berries and other fresh yield [27]. In addition to microbial inactivity, cap can be delayed enzymatic browning in cut fruit by modifying polyphenoloxidation activity [28]. In addition, plasma exposure can increase the bioavailability of antioxidant compounds such as phenol and flavonoids, possibly improving the nutritional quality of treated dividends [29]. These findings suggest that CAP can serve as a safe alternative for chlorine -based washing solutions usually used in the fresh production industry.

2.3 Cereal Grains and Nuts

Grain grains and nuts are often contaminated by mold and micotoxins, leading to severe food security risk and financial loss. Cap has shown promising consequences for neutralizing fungal spores on wheat, rice, corn and peanuts, as well as micotoxin such as afflatoxin and deoxinivalenol [30]. Unlike thermal agents, the cap receives this processing, without affecting the germination speed or nutritional structure of grain. In addition, plasma treatment has been shown to improve hydration of seeds and germination efficiency, which may have double benefits in both food safety and agricultural productivity [31].

2.4 Packaged and Processed Foods

CAP can also be used on indirectly packed foods, which makes it specially prepared for food, minimal processed products and foods with extended durability requirements. Plasma treatment in the package is shown to reduce the contamination of bacteria in bread, cheese and chopped daily meat, as well as maintain product freshness [32]. In addition, the plasma treatment of packaging films before sealing sterility increases and reduces the risk of relapse [33]. Such common approaches show capacity as an integrated solution for both food security and packaging quality.

2.5 Summary of Applications

Overall, the hood has shown widespread praise in several food categories. The ability to disable pathogens, expand durability and maintain quality emphasizes its ability as a revolutionary technology for the food industry. However, the effectiveness of plasma treatment depends on many factors, including food matrix, microbial type, plasma parameters and treatment conditions. Continuous research and adaptation are necessary to ensure that cap can be used in continuous different industrial surroundings..

3. Effects of Cold Atmospheric Plasma on Food Quality

While the antimicrobial effectiveness of cold atmospheric plasma (CAP) is widely documented, its impact on sensory and nutritional quality on foods is equally important for consumer acceptance and industrial application. Protective technologies should not only ensure safety, but also maintain or improve desirable properties such as appearance, texture, taste and nutrition composition. Research has shown that CAP can have both positive and negative effects on these properties, depending on the type of food matrix and treatment parameters.

3.1 Color and Appearance

Color is one of the most important sensory properties that affect the freshness and quality of the quality. Plasma exposure can change the color of the surface due to oxidative changes in pigments such as meat and anthocyanin in meat and vegetables. For example, short plasma agents can stabilize light red color of fresh meat by maintaining oxymoglobin, while excessive risk can promote chemo -lobinde formation, which can cause discomfort [34]. Similarly, in fruits and vegetables, Cap has been informed to reduce polyphenoloxidation enzyme [35] and reduce enzyetic browning in chopped apples and potatoes. Thus, careful adaptation of treatment time and plasmainensity is necessary to preserve natural color characteristics.

3.2 Texture and Structural Integrity

The effect of the cap on the food texture varies depending on the product. In fresh dividends, plasma -thread radical cell wall can cause microscopic modifications in components, sometimes a pioneer and delayed soft [36] for firmer tissue structures. In meat, medium cap exposure usually preserves better texture than thermal agents, as protein is minimized and the water loss is minimized [37]. However, long -term treatment or extremely high emission power can induce protein cross binding or lipidoxidation, and potentially affect tenderness and juice. Therefore, balanced microbial inactivity with minimal structural changes is an important challenge.

3.3 Flavor and Aroma Flavor

A complex feature affected by volatile compounds, lipidoxidation products and myelard reaction intermediate. Plasma treatment can sometimes induce less oxidative changes in lipids, resulting in aldehyde or ketones that change the perception of taste [38]. Nevertheless, most studies indicate that when CAP is used under custom conditions, sensory panels do not detect a significant difference between meat, dairy or fresh dividend [39]. Interestingly, in some cases, CAP treatment is reduced off flax due to microbial malfunctions, indirectly improving the quality of the general taste.

3.4 Nutritional Composition

Nutrient stability is a vital aspect of food preservation. Plasma treatment generally has minimal impact on macronutrients such as proteins, carbohydrates, and lipids, although some structural modifications occur as discussed earlier. More attention has been paid to micronutrients such as vitamins and antioxidants, which are more sensitive to oxidation. Studies have reported moderate reductions in ascorbic acid and tocopherols after plasma treatment, especially with longer exposure times [40]. However, these losses are typically lower than those observed in conventional thermal pasteurization. In addition, CAP may enhance the extractability of bioactive phytochemicals, including phenolic compounds and flavonoids, thereby improving antioxidant capacity in plant-based foods [41].

3.5 Consumer Acceptance

Ultimately, the success of any preservation technology depends on consumer perception. Surveys indicate that consumers are generally receptive to plasma-treated foods when the benefits of safety, freshness, and reduced chemical preservatives are clearly communicated [42]. Transparent labeling and regulatory approval will further strengthen consumer trust and facilitate market adoption.

4. Challenges and Safety

Concerns Despite the promising potential of cold atmospheric plasma (CAP) in food preservation, several challenges and safety concerns must be addressed before the technology can achieve widespread industrial adoption. These issues span technical limitations, toxicological considerations, regulatory frameworks, and consumer acceptance.

4.1 Process Standardization and Scale-Up

One of the foremost challenges in CAP technology is the lack of standardized treatment protocols. Plasma properties are highly dependent on input parameters such as gas composition, flow rate, discharge power, electrode configuration, and treatment duration [43]. Variability in these factors makes it difficult to compare results across studies and to establish universally applicable processing guidelines. Additionally, scaling plasma systems from laboratory prototypes to industrial-scale units presents engineering challenges, particularly in maintaining uniform plasma exposure over large surface areas or bulk food products [44].

4.2 Formation of By-Products

While CAP is generally considered a clean technology, concerns have been raised about the possible formation of undesirable by-products. Plasma–food interactions can lead to the generation of oxidized compounds, such as lipid peroxides, aldehydes, and nitrites [45]. Although most studies indicate that these compounds remain within safe limits, long-term toxicological evaluations are limited. In packaged foods, plasma exposure may also induce chemical changes in packaging polymers, potentially releasing low-molecular-weight compounds into the product [46]. Thus, more research is needed to fully assess the safety implications of plasma-derived residues.

4.3 Toxicological and Health Aspects

The safety of plasma-treated foods is a critical prerequisite for regulatory approval. Current evidence suggests that CAP does not introduce harmful chemical residues at levels of concern, and several animal feeding studies have shown no adverse health effects associated with consumption of plasma-treated products [47]. However, comprehensive toxicological assessments are still lacking, especially regarding the cumulative effects of long-term consumption. Particular attention must be given to vulnerable populations, including children, pregnant women, and individuals with chronic illnesses, before CAP can be universally accepted as safe.

4.4 Regulatory Frameworks

At present, CAP is not explicitly recognized in food regulations by major international agencies such as the U.S. Food and Drug Administration (FDA) or the European Food Safety Authority (EFSA). The absence of a clear regulatory framework limits commercial adoption and restricts investment in plasma-based technologies [48]. To facilitate acceptance, regulatory bodies require robust data on efficacy, toxicology, and consistency of treatment outcomes. Collaborative efforts among researchers, industry stakeholders, and policymakers will be essential to develop harmonized standards for plasma-treated foods.

4.5 Consumer Perception and Market Acceptance

Beyond technical and regulatory issues, consumer perception plays a decisive role in the success of novel food technologies. Public acceptance of CAP-treated foods may be hindered by a lack of awareness and possible negative associations with the word "plasma" or "radiation." Studies indicate that when consumers are informed about the safety, non-thermal nature, and chemical-free benefits of CAP, acceptance levels increase substantially [49]. Transparent labeling, educational campaigns, and communication of health and sustainability benefits will therefore be critical to building consumer trust.

5. Future Perspectives

Cold atmospheric plasma (CAP) has demonstrated remarkable potential as a non-thermal, sustainable, and multi-functional food preservation technology. Nevertheless, its industrial adoption will depend on addressing current limitations and advancing several key research and development areas. Future perspectives can be grouped into technological innovation, integration with complementary approaches, sustainability, and regulatory advancement.

5.1 Technological Innovation and Process Optimization

The design of plasma reactors and the control of discharge parameters will play a central role in determining the success of CAP applications. Future research should focus on developing standardized plasma systems capable of delivering uniform treatments across a variety of food matrices [50]. The use of advanced sensors and real-time monitoring of reactive species could improve process consistency and reproducibility. Furthermore, miniaturized and portable plasma devices may enable decentralized applications, such as in local food markets or small-scale industries.

5.2 Integration with Other Technologies Combining

CAP with complementary non-thermal preservation methods represents a promising avenue for enhancing efficacy while minimizing quality degradation. For example, synergistic effects have been reported when CAP is combined with ultraviolet (UV) light, high-pressure processing (HPP), pulsed electric fields (PEF), or antimicrobial coatings [51]. Such hybrid approaches could reduce treatment times, lower energy costs, and provide multi-barrier protection against foodborne pathogens. Additionally, integration with smart packaging systems could allow plasma-activated materials to deliver continuous antimicrobial action during storage and distribution.

5.3 Sustainability and Energy Efficiency

One of the strongest drivers for adopting plasma technology is its alignment with global sustainability goals. Unlike traditional chemical sanitizers, CAP generates antimicrobial activity without leaving harmful residues and can operate using only ambient air as a feed gas [52]. Future studies should evaluate the energy efficiency of plasma systems compared to conventional preservation technologies and explore the use of renewable energy sources to power plasma units. Life-cycle assessments will be crucial in demonstrating the environmental benefits of CAP to industry and regulators.

5.4 Regulatory and Safety Frameworks

The development of clear regulatory frameworks will be essential for market acceptance. Future efforts should focus on generating comprehensive toxicological data, including long-term studies on plasma-treated foods, to support applications to international regulatory bodies such as the FDA and EFSA [53]. Establishing internationally harmonized guidelines and safety standards will accelerate commercialization and increase consumer confidence in plasma-based food technologies.

5.5 Industrial and Commercial Prospects

Over the next decade, it is expected that CAP will move beyond pilot-scale studies into large-scale industrial applications. Early adoption may occur in high-value food sectors such as ready-to-eat meals, minimally processed produce, and organic foods, where consumer demand for chemical-free preservation is high [54]. Collaboration between researchers, equipment manufacturers, and food processors will be vital in translating laboratory successes into practical, cost-effective industrial solutions.

6. Conclusions

Cold Atmospheric Plasma (CAP) has emerged as one of the most promising non-thermal preservation technologies in the food industry. The unique combination of broad -spectrum antimicrobial activity, minimal impact on sensory and nutritional quality, and environmentally friendly operation separates it from a traditional conservation perspective. Over the past decade, research has shown successful applications of cap in various food categories, including meat, dairy products, fruits, vegetables, grains and packed foods. It is important that plasma treatment not only improves microbial safety, but also provides potential improvement in durability, packaging functionality and even nutritional properties in some cases. Still, despite these advances, many challenges remain. Lack of standardized processing parameters, potential formation of oxidative products, limited toxicity data and the absence of clear regulatory approval currently prevents plasma technologies. In addition, consumers' opinions and acceptance represent an extra layer of complexity that must be carefully taken through transparent communication and consciousness strategies. In the future, Hood's approaches are very encouraging. Other theft techniques will strengthen their role in modern food processing adapted to continuous technological innovation, integration and stability goals. Cooperative efforts between researchers, equipment developers, food processors and policy makers will be important for removing relevant obstacles and ensuring safe, efficient and costs -affected plasma systems. With proper adaptation and regulatory support, CAP has the opportunity to become mainstream industrial equipment and is a basis in transitions for safe, cleaner and more durable food safety strategies around the world.

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