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Cold plasma: Unveiling its impact on hydration, rheology, nutritional, and anti-nutritional properties in food materials – An overview

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A R T I C L E I N F O

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A B S T R A C T

Non-thermal technologies, primarily employed for microbial inactivation and quality preservation in foods, have seen a surge in interest, with non-thermal plasma garnering particular attention. Cold plasma exhibits promising outcomes, including enhanced germination, improved functional and rheological properties, and microorganism destruction. This has sparked increased exploration across various domains, notably in hydration and rheological properties for creating new products. This review underscores the manifold benefits of applying cold plasma to diverse food materials, such as cereal and millet flours, and gums. Notable improvements encompass enhanced functionality, modified color parameters, altered rheological properties, and reduced anti-nutritional factors. The review delves into mechanisms like starch granule fragmentation, elucidating how these processes enhance the physical and structural properties of food materials. While promising for high-quality food development, overcoming challenges in scaling up production and addressing legal issues is essential for the technology's commercialization.

1. Introduction

Various properties play a crucial role in ensuring the quality and safety of foods. Among these properties, hydration, rheological, and nutritional properties often require improvement, while properties such as anti-nutritional factors need to be minimized to the greatest extent possible. To achieve these desired food properties, various technologies have been adopted and applied.

Plasma is described as a partially or wholly ionized state of matter that exists as a gas. In this state, some or all of the gas particles have lost or gained electrons, resulting in the presence of free electrons and ions. The transition from a solid to a liquid and then to a gas occurs as energy input is increased. However, when the energy input is raised beyond a certain threshold in the gaseous state, it leads to the ionization of gas molecules, creating a plasma state. This ionization process involves the separation of electrons from atoms or molecules (Fernández et al., 2013). It consists of several reactive species such as positive and negative ions, high energy electrons, free radicals, photons and many others. The key characteristic of non-equilibrium cold plasma, emphasizing its capability to produce a diverse mix of biologically active agents, including reactive oxygen species (ROS) and reactive nitrogen species (RNS), all while maintaining a temperature close to ambient conditions. This feature makes it suitable for safe applications to biological materials, including foods. It's worth noting that the composition and concentration of these reactive species within the plasma can vary significantly, influenced by factors such as the type of gas used to induce the plasma, the configuration of the plasma source, the amount of power applied to the gas, the treatment duration, and the humidity levels in the environment (Moiseev et al., 2014). Certainly, the generation of reactive oxygen species (ROS) can vary depending on the gas used in non-thermal plasma processes. Some examples of ROS associated with antimicrobial activity and inactivation cascades, based on different gases are ozone (O_3), superoxide Anion ($O_2^{\bullet-}$), singlet Oxygen ($^1O_2$), hydroperoxyl ($HO_2^{\bullet}$), hydroxyl radical ($^{\bullet}OH$), alkoxyl ($RO^{\bullet}$), peroxyl ($ROO^{\bullet}$), carbonate anion radical ($CO^{3\bullet-}$). Similarly, some of reactive nitrogen species such are include nitric oxide ($NO^{\cdot}$), nitrogen dioxide radical ($^{\cdot}NO_2$), peroxynitrite ($ONOO^-$), peroxynitrous acid (OONOH), and alkylperoxynitrite (ROONO) (Shashi K. Pankaj & Keener, 2017).

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Reactive species possess the capability to combat microorganisms, including bacteria and viruses, thereby rendering them inactive and impeding their ability to survive (Mendes-Oliveira et al., 2019; Misra et al., 2011; Umair et al., 2022).

Indeed, cold plasma (CP) technology is relatively newer when compared to traditional thermal methods, primarily used for curing and bonding polymers and spread to various applications in different sectors before finding its way into the food industry (Ucar et al., 2021). It has proven promising and has been well-utilized for various food applications over the past two decades. As a non-thermal technique, cold plasma offers several advantages for the food industry, including its ability to modify, decontaminate, and enhance packaging without the need for excessive heat. The reactive plasma species acted on variety of foods in distinct mechanisms proves product with safe, stable, economical and zero wastage (Yang et al., 2009). While non-thermal plasma technology offers advantages in improving the quality of grain flours, it comes with some challenges, including the adoption of non-thermal plasma technology may involve significant upfront investments in equipment and infrastructure, which can be a barrier for some businesses and handling high-voltage equipment and plasma processes requires stringent safety measures to protect personnel and ensure safe operation. Effective operation and maintenance of plasma systems necessitate trained and skilled personnel who understand the technology and safety protocols (Kruk et al., 2011; Yun et al., 2010). Based on recent scientific reports, it has been shown that plasma treatment can also be used to modify starch. This interaction between plasma species and starch can result in three distinct mechanisms: cross-linking, depolymerization, and plasma etching. These mechanisms have been responsible for various surface modifications in biodegradable polymers. In addition to these three mechanisms, the introduction of functional groups can also play a role in modifying starch (Thirumdas, Trimukhe, et al., 2017). It was vitally applied to modify the functionality of flours and starches for better product quality while retaining nutritional profile apart from decontamination and microbial reduction of fruits and vegetables, water, disinfection of food packaging materials, etc (Thirumdas et al., 2015). Reactive species generated from plasma by collision of electrons does prominent effect on decreasing toxic or anti-nutritional factors (Shashi K. Pankaj et al., 2018). Moreover, cold plasma has been extended to packaging materials, including gelatin-based films, which can result in heightened surface hydrophobicity and surface roughness of the film, while maintaining unchanged water vapor permeability after plasma treatment with various gases such as O_2, N_2, air, Ar, and ethanol-argon (EtOH-Ar) (Ledari et al., 2020). Grain flours with enhanced dough characteristics and other flow properties are highly sought after in the bakery industry. Several methods, including microwave cooking, extrusion, germination, and pre-gelatinization, have been used to improve these properties reported by Gong et al., (2018); Jisha et al., (2008); Rao et al., (2021), but they come with disadvantages such as longer processing times and potential heat-sensitive nutrient loss. To address these challenges, non-thermal plasma technology has been adopted to achieve excellent quality characteristics in grain flours. This innovative approach offers advantages in terms of processing efficiency and nutrient retention, making it a promising solution for the industry.

The rheological characteristics of various cereals and other powders were treated with cold plasma were reviewed. The changes of cold plasma effect on hydration, bioactives, nutritional properties and anti-nutritional factors of different grain flours and other products are well discussed and documented in this review.

2. Plasma effect on hydration properties of foods

The hydration properties of a food material refer to its capacity to retain and hold water or oil within its structure. This retention is facilitated by polar, hydrogen-bonding, and hydrophobic interactions that occur within the food matrix. Furthermore, water can interact with other food ingredients, contributing to various properties and characteristics of the food product. The characteristics of food are altered by these interactions (Kasaai, 2014) and mode of action of plasma species were depicted in Figs. 1 and 2. Most food materials undergo interactions with water during processing, and understanding these interactions is crucial for further processing. These interactions can lead to changes in the characteristics of the food material, affecting its texture, consistency, flavor, and other attributes. Therefore, having knowledge of how food materials behave when exposed to water is essential for achieving desired outcomes in food processing and product development. The impact of cold plasma on the hydration properties of various substances was investigated, and the outcomes of these studies have been catalogued in Table 1 for easy reference and analysis.

2.1. Flour hydration properties

2.1.1. Water holding capacity (WHC)

Water holding capacity (WHC), encompassing bound water, capillary water, hydrodynamic water, and physically entrapped water, serves as a comprehensive indicator of a substance's capacity to absorb and retain water in defiance of gravitational forces (Chaple et al., 2020). This also refers to the quantity of water that a sample can retain without experiencing stress or excessive loss. It plays a fundamental role in shaping the texture of various food products, including those in the bakery and meat categories. It directly influences factors such as moisture content, tenderness, juiciness, and overall mouthfeel in these food items. Cold plasma treatment increased WHC with wheat flour, jack fruit seed flour, and parboiled rice flour (Chaple et al., 2020; Joy et al., 2022; Sarangapani et al., 2016). Starch hydrolytic depolymerization takes place during plasma treatment, which accounts for the increase in water-holding capacity (WHC). Similar results have been observed in the cases of pollock myofibrillar protein and peanut protein, where plasma treatment led to increased WHC, likely due to the hydrolytic depolymerization of starch (Ji et al., 2018; Miao et al., 2020). There was an observed increase in water-holding capacity (WHC) as plasma voltage increased, and higher voltage settings were found to facilitate the formation of disulfide bonds. The formation of disulfide bonds is a crucial component in the process that contributes to the production of protein gels (Misra et al., 2015). Conversely, the reduction in water-holding capacity (WHC) observed in quinoa flour at high voltage may be attributed to the reduction of hydroxyl groups.

2.1.2. Water binding capacity (WBC)

Water binding capacity refers to a food product's ability to retain moisture due to its hydrophilic (water-attracting) properties. This characteristic illustrates how flour, for example, can interact with water during the preparation of dough and paste. A higher water binding capacity in a food ingredient can contribute to improved moisture retention and texture in the final product (Joy et al., 2022). The surface morphology of the products is altered by cold plasma, which results in improved hydration characteristics. This was accomplished by the creation of fissures, fractures, and pores (Kalaivendan et al., 2022). The water-binding capacity of wheat flour increased greatly when treated as flour and not as grain. Increasing the surface area of the sample, which initially interacts with plasma, alters the hydration properties of flours. This effect may be taken into account when designing processes to meet the required functionality. The significant increase of WBC was found in food materials such as jack fruit seed flour and parboiled rice flour (Joy et al., 2022; Sarangapani et al., 2016) and also found subtle increase in wheat flour (Chaple et al., 2020) due of the substance's hydrophilic characteristics, hydroxyl groups naturally form hydrogen bonds with water. WBC of starch was reported to increase significantly after cold plasma treatment (Banura et al., 2018; Zhou et al., 2019). The depolymerization of polysaccharides caused by plasma reactive species, which results in the creation of smaller pieces with stronger water affinity, may be linked to an increase in WBC (Thirumdas, Trimukhe, et al., 2017).

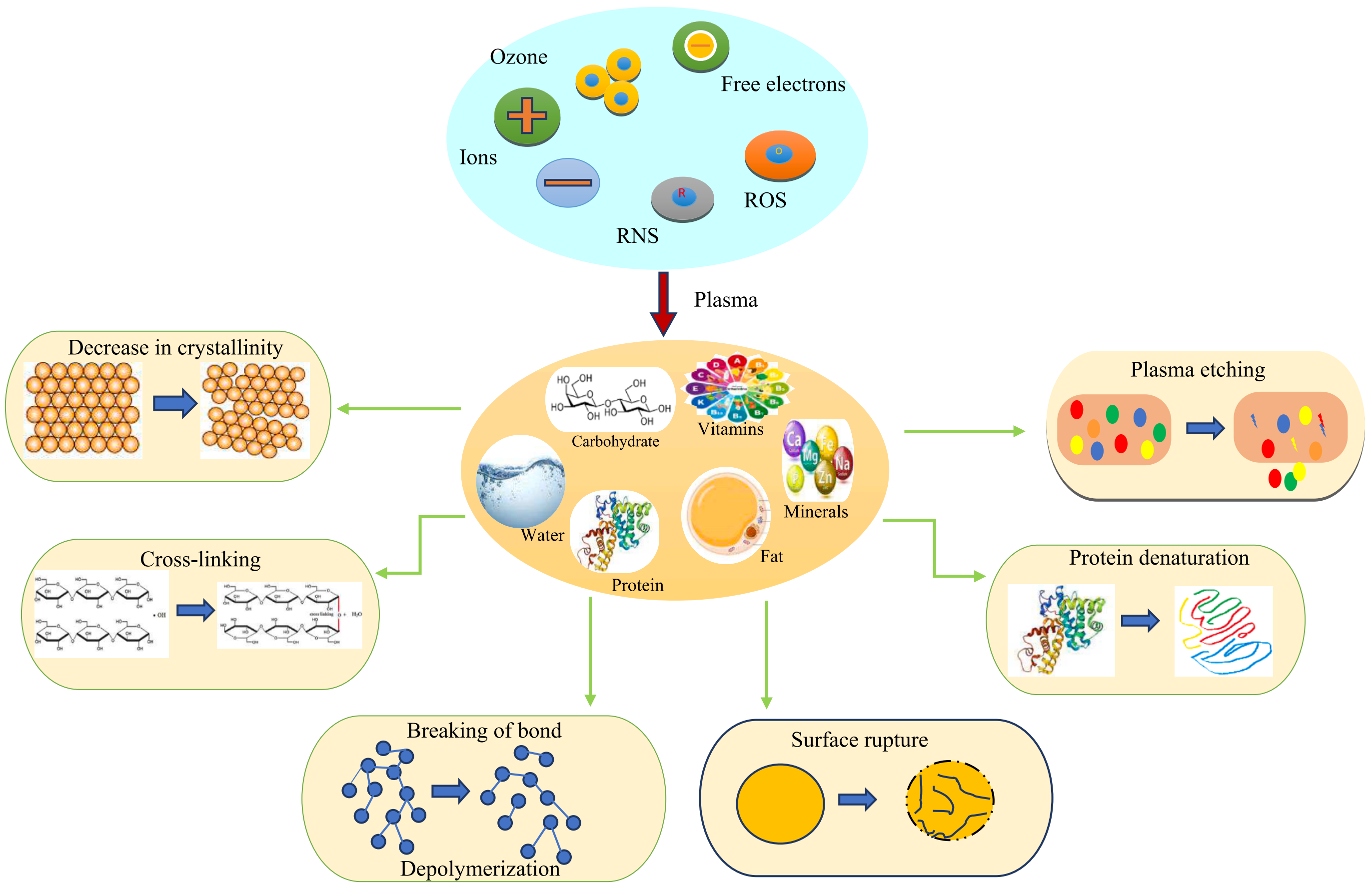

Fig. 1. Effect of cold plasma on food components.

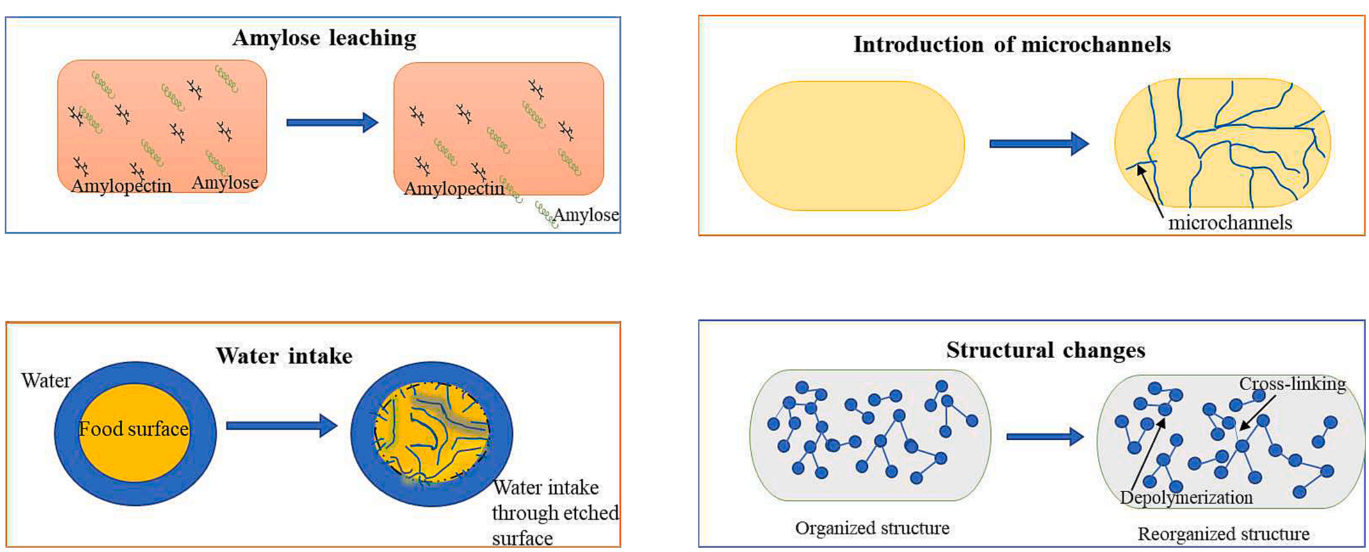

Fig. 2. Changes in properties of food by applying cold plasma.

2.1.3. Oil holding capacity (OHC)

Oil holding capacity refers to the amount of oil that a sample can retain without undergoing excessive stress or releasing the oil. This property is important in various food and culinary applications, where the ability to retain oils can impact the texture and flavor of the final product. High oil holding flour has the potential to be employed in food items to preserve taste, boost acceptability, and lengthen storage life. For baking or cooking with oil, these characteristics are needed (Sarangapani et al., 2016). The significant increase in OHC with quinoa flour and parboiled rice flour with plasma was observed (Sarangapani et al., 2015; Zare et al., 2022). The non-polar amino acid concentration and protein content and bulk density of protein powder obtained from cereal flour may affect the OHC (Jaddu, Pradhan, et al., 2022). Cold plasma had little impact on the OHC of wheat flour. In contrast, there has been some documented OHC alterations, but the changes were not substantial (Kalaivendan et al., 2022). Yet the values after treatment

Table 1
Effect of plasma on hydration properties of different foods.

Food Material	Parameters analyzed	Source of plasma discharge	Voltage/power applied and time	Key outcomes
Rice starch	Water absorption index Water solubility index Swelling power Amylase content Water absorption of starch Fat absorption of starch	Bell jar type	40 W – 5, & 10 min 60 W – 5, & 10 min	Water and fat absorption increased Water absorption index increased with increase in power but decreased with increase in timeSwelling power and water solubility index increased with increase in power but decreased with increase in time (Thirumdas et al., 2017)
Wheat flour	Water holding capacity Water binding capacity Oil holding capacity Water absorption index Water solubility index Swelling power	Dielectric barrier discharge	80 kV – 5, 10, 20, & 30 min	Oil and water holding capacity increased with treatment time water binding capacity increased with plasma treatment water absorption index, water solubility index decreased with increase in treatment timeswelling power decreased with plasma treatment (Chaple et al., 2020)
Pearl millet flour	Swelling capacity Solubility Water absorption capacity	Atmospheric pressure jet	40 kV – 5, 10, & 15 min 45 kV – 5, 10, & 15 min	Swelling capacity increased, water absorption capacity increased, and solubility increased (Lokeswari et al., 2021)
Pearl millet flour	Water absorption capacity Oil absorption capacity	Multi pin electric discharge	20 kV – 10, 20 min 25 kV – 10, 20 min 30 kV – 10, 20 min	Increased in WAC and OAC with treatment time and voltage (Sarkar et al., 2023)
Little millet flour	Water absorption capacity Oil absorption capacity Swelling index Solubility capability	Multi pin electric discharge	13 W – 10, 20, & 30 min 24 W – 10, 20, & 30 min	Water absorption capacity increased, oil absorption capacity increased, swelling index increased, solubility capability increased (Jaddu, Pradhan, et al., 2022)
Kodo millet flour	Water absorption capacity Oil absorption capacity Swelling index Solubility capacity	Multi pin electric discharge	Vary in voltage and time from 10 to 30 kV and for 10 to 30 min	Increase in WAC after 15 kV and 20 min Increased in OAC with treatment time and voltage upto 16 kV than slightly decreased Increased in SI and SC with treatment time and voltage upto 16 kV than slightly decreased (Jaddu, Abdullah, et al., 2022a, Jaddu et al., 2022b)
Quinoa flour	Water absorption index Water solubility index Swelling power Water holding capacity Oil holding capacity	Dielectric barrier discharge	50 kV – 5&10 min 60 kV – 5&10 min	Oil holding capacity increased with treatment time, water holding capacity decreased, water absorption index decreased, water solubility index decreased, swelling power increased with increasing time and decreased with increasing voltage (Zare et al., 2022)
Parboiled rice flour	Water holding capacity Water binding capacity Oil holding capacity Water absorption index Swelling capacity Water solubility index	Low-pressure dielectric barrier discharge	30 W – 5,10,15 min 40 W – 5,10,15 min 50 W – 5,10,15 min	Water holding capacity, water binding capacity, oil holding capacity increased with increasing power and time (Sarangapani et al., 2016)
Fenugreek seed flour	Water binding capacity Swelling index	Dielectric barrier discharge	80 kV – 30 min	Fenugreek galactomannan extraction increased after plasma treatmentWater binding capacity, swelling index increased with treatment (Rashid et al., 2020)
Jackfruit seed flour	Oil binding capacity Water binding capacity Water holding capacity	Pin-to-plate electric discharge	170 V – 5,10,15 min 200 V – 5,10,15 min 230 V – 5,10,15 min	Water holding capacity and binding capacity increased with applied high voltage and treatment time Oil binding capacity increasedWater absorption index, water solubility index, swelling power increased with time (Joy et al., 2022)

(continued on next page)

Table 1 (*continued*)

Food Material	Parameters analyzed	Source of plasma discharge	Voltage/power applied and time	Key outcomes
	Water Absorption Index Water Solubility Index Swelling power			
Lotus root starch	Solubility Swelling power	Dielectric barrier discharge	40 V – 60, 90, 120 s	Solubility increased with temperature and timeSwelling power increased with temperature and time (Sun et al., 2023)
Mango seed kernel starch	Oil binding capacity Water binding capacity Water Absorption Index Water Solubility Index Swelling power	Pin to plate electric discharge	170 V – 15, 30 min 230 V – 15, 30 min	Water and oil binding capacity increased with timeWater absorption index, water solubility index, swelling power increased with time and temperature (Kalaivendan et al., 2022)
Soybean protein isolate	Solubility	Dielectric barrier discharge	40 kV – 1, 2, 5 10 min	Solubility decreased in a increasing trend with increasing time (Zhang et al., 2021)
Pollock myofibrillar protein	Water holding capacity	Dielectric barrier discharge	10, 20, 30, 40, 50 and 60 kV – 10 min	WHC increased by applied high voltage (Miao et al., 2020)
Peanut Protein	Solubility Water holding capacity	Dielectric barrier discharge	35 V – 1, 2, 3, 4 min	Water holding capacity increased but decreased after 2 min treatment time Solubility increased upto 3 min treatment time, decreased for 4 min (Ji et al., 2018)
Peanut meal	Water holding capacity	Dielectric barrier discharge	35 V – 1, 2, 3, 4, 5 min.	WHC increased, highest WHC was observed for 2 min treatment (Ji et al., 2022)
Aria starch	Water solubility index Water absorption index	Dielectric barrier atmospheric	7 kV – 15 min 10 kV – 15 min 14 kV – 15 min 20 kV – 15 min	Water solubility index increased with increase in voltageWater absorption index increased with increase in voltage (Paula et al., 2021)
Red adzuki bean starch	Swelling power Solubility	Dielectric barrier discharge	40 V – 1,5,10 min	Solubility increased with time and temperatureSwelling power decreased with time and temperature (Ge et al., 2021)
Corn starch	Swelling power Solubility	Dielectric barrier discharge	40 V – 1, 3, 9 min	Solubility increased with time and temperatureSwelling power decreased with time and temperature (Ge et al., 2022a)
Rice starch	Solubility Swelling power	Dielectric barrier discharge	40 V – 1,3,6,9 min	Solubility increased with treatment timeSwelling power increased with treatment time (Ge et al., 2022b)
Taro starch	Solubility	Dielectric barrier discharge	30 kV – 2 min 32 kV – 4 min 34 kV – 8 min	Solubility was greatly enhanced at high voltage (Gupta et al., 2023)
Mung bean starch	Solubility Swelling power	Dielectric barrier discharge	40 V – 1, 3, 9 min	Solubility increased with treatment timeSwelling power decreased with treatment time (Shen et al., 2021)
Xanthan gum	Water holding capacity Oil holding capacity	Bell jar-type	50 W – 15, 20 min 60 W – 15, 20 min	OHC increased except for 50 W – 15 min, WHC increased with time and power (Bulbul et al., 2019)

were higher than the untreated ones. This might be due to less protein denaturation during plasma treatment. Reduced protein and starch hydrophilic groups might be the reason for the slight increase in the OHC (Zare et al., 2022). OHC is generally due to the entrapment of oil within the starch granules, and starch does not possess any non-polar compounds as similar to proteins (Abu et al., 2006).

2.2. Gel hydration properties

Gel hydration qualities reflect water intake during heat treatment, which affects starch gelatinization (Chaple et al., 2020). The hydrophilic property of the ingredients, which is again influenced by their physical and chemical structure, is what gives food matrices their gel-hydrating capabilities. Food matrices' hydration characteristics are significantly impacted by interfering with their structure. Many alterations in water absorption index, water solubility index, swelling power, which might be the results of the surface morphological alterations brought by cold plasma treatment.

2.2.1. Water absorption index (WAI)

The determination of WAI is significantly influenced by polar groups found in proteins, polysaccharides, and other key constituents. There had been reports of both an increase and a reduction in WAI by various authors. The depolymerization of amylose and amylopectin leads to the production of simple sugars, which have the ability to absorb water at their surfaces, consequently leading to an increase in the Water Absorption Capacity (WAC). Thirumdas, Kadam, et al., (2017) reported that plasma etching is suggested as one of the reasons for the increased WAC value of plasma-treated starch compared to untreated starch. Plasma treatment alters the surface structure of the starch particles, making it easier for water and heat to enter the starch granules. This alteration contributes to an improvement in the functional characteristics of the starch. Scanning Electron Microscope (SEM) images clearly demonstrate that the structure of the starch particles undergoes significant alterations during plasma treatment in various materials such as rice flour, little millet and kodo millet flours (Jaddu, Abdullah, et al., 2022a; Jaddu, Pradhan, et al., 2022; Thirumdas, Deshmukh, et al., 2016). This alteration leads to the formation of micro channels, which ultimately results in an increase in WAC. Micro channels facilitate the entry of water into the starch granules. An observed trend reveals that as the voltage of the plasma treatment is escalated, there is a noticeable tendency toward a marginal reduction in the Water Absorption Capacity (WAC) of kodo millet starch (Sonkar et al., 2023). The increment in WAI in mango seed kernel starch was observed (Kalaivendan et al., 2022), whereas decrease in WAI values after cold plasma treatment in quinoa flour (Zare et al., 2022). Increase in water absorption was mainly due to formation of cross linkages between starch molecules (Lokeswari et al., 2021). Thirumdas, Deshmukh, et al., (2016) also found that generated plasma can induce the starch depolymerization and formation of carboxylic starch which was caused by partly oxidization. Due to which starch molecules were damaged, there by rice flour absorbed more water absorption. Hydroxyl radicals, ozone, and other plasma species might not even penetrate through the interior surface of grains. But instead, it causes surface-related chemical changes, which results in changes in WAI (Chaple et al., 2020). A decrease in WAI might be reasoned by protein denaturation. Protein denatures and makes a surface barrier over starch granules to stop their depolymerization and therefore lower their WAI (Zare et al., 2022). At longer treatment times, WAI is thought to have reduced mostly due to polar group reduction.

2.2.2. Water solubility index (WSI)

Solubility is a crucial parameter for assessing the overall quality of final products, including health drinks, energy mixes, and etc. Previous researchers have shown that solubility increases as both voltage and exposure time rise during the treatment process. There were many reports that revealed an increase in WSI in food substances as an impact of cold plasma (Jaddu, Abdullah, et al., 2022a, Jaddu et al., 2022b). Many researchers observed an increase in WSI after cold plasma treatment (Joy et al., 2022; Sarangapani et al., 2016; Zhou et al., 2019). By modifying the functional group composition of material surfaces, plasma may affect their wettability. Plasma reactive species have also been discovered to enhance polymer oxygen to carbon (O/C) and nitrogen to carbon (N/C) ratios, resulting in higher surface hydrophilicity (Rashid et al., 2020). The oxidation and molecular degradation of starch by plasma reactive species improved the solubility (Bie et al., 2016). Gel hydration properties depend upon heating temperature. High temperatures may enhance starch solubility. This might be due to the fact that high temperatures promote full emigration of amylose out from crystal surface of amylopectin, boosting leaching and hence increasing solubility (Ge et al., 2021; Sun et al., 2023). Plasma increases the exposure of active sites, allowing them to interact with more water molecules (Zhang et al., 2021). This is followed by shorter cooking times as a result of surface etching and the opening up of the uppermost fibrous husk following plasma treatment (Thirumdas, Trimukhe, et al., 2017).

Another key factor in enhancing the solubility of starch lies in the disruption of its crystalline structure. Starch granules possess a semi-crystalline structure, consisting of both amorphous and crystalline regions. Cold plasma treatment has the ability to disturb this crystalline arrangement by inducing partial fragmentation or degradation. This disruption exposes a greater surface area of amorphous regions, which readily dissolve in water compared to the crystalline sections. The reduction in crystalline structure was further verified through X-Ray diffractometer analysis, and the findings were documented in a study conducted by Jaddu, Pradhan et al. (2022). Dielectric Barrier Discharge (DBD) plasma treatment induces structural alterations in taro starch, notably augmenting accessibility to amorphous regions, while concurrently imparting heightened hydrophilicity through the introduction of polar functional moieties, such as hydroxyl, carbonyl, or carboxyl groups, onto the starch granule surface. These molecular modifications synergistically enhance the starch's propensity for water interaction, thus facilitating superior hydration and granule swelling, ultimately leading to heightened solubility. Additionally, plasma treatment likely optimizes gelatinization dynamics and elevates the substrate's susceptibility to enzymatic hydrolysis. In light of these discernible effects, it can be inferred that plasma-treated taro starch exhibits augmented solubility, rendering it a judicious choice as an ingredient in frozen food formulations when compared to alternative physical modification methodologies (Gupta et al., 2023).

On the contrary, decrease in WSI was reported in quinoa flour due to denaturation proteins acts as a barrier and stops the cross linking of starch molecules at higher voltages.

2.2.3. Swelling power (SP)

Swelling power or capacity is a parameter that quantifies the extent of interaction among starch chains within both the crystalline and amorphous regions of starch granules. This interaction is influenced by several factors, including the ratio of amylose to amylopectin in terms of their molecular weight, branch length, and degree of branching. Changes in these characteristics can have a significant impact on the swelling power of starch. Indeed, the swelling capacity (SC) of starch is closely related to its interaction with water. Starch is a complex carbohydrate composed of two types of molecules: amylose and amylopectin. When starch comes into contact with water, several important processes occur; firstly it can absorb water molecules through hydrogen bonding. This leads to the swelling of starch granules as water molecules enter the granules and interact with the starch molecules. Secondly, as water is absorbed, starch undergoes gelatinization. During gelatinization, the starch granules absorb water and swell, causing them to lose their crystalline structure. This results in the formation of a gel-like substance. Plasma generated with high voltage leads to increase of swelling capacity (Chaple et al., 2020). The swelling capacity serves as a metric to quantify the extent of interaction between the crystalline and amorphous states of starch. The capacity of starch to capture and hold water within its structures both before and after gelatinization is swelling power (Sarangapani et al., 2016). An increase in the swelling power was noted in both mango kernel starch and jackfruit seed powder (Joy et al., 2022; Kalaivendan et al., 2022). Conversely, a decrease in swelling power was observed after subjecting parboiled rice flour to cold plasma treatment (Sarangapani et al., 2016). Swelling power is essentially an amylopectin feature that is inhibited by amylose (De La Hera et al., 2013). Nevertheless, the presence of additional non-starch components seems to impact the swelling pattern of amylopectin, and its capacity to swell may be hampered by the other structural ingredient. As it was proved, plasma treatment increases amylose permeability from the amorphous area, increasing starch solubility (Sun et al., 2023). Starches with higher amylose concentrations had lower SP than those with lower amylose contents (Thirumdas, Trimukhe, et al., 2017). Swelling power of cold plasma treated starch increased, but combining it with temperature swelling power decreases. The increase in swelling power might be due to the molecular reorganization promotes starch hydration (Sun et al., 2023).

2.2.4. Foaming capacity and emulsification ability

The foam capacity of a protein is a measure of the protein's ability to create interfacial area within a foam (Chandra et al., 2015). Foam, in this context, is a colloidal system composed of numerous gas bubbles trapped within a liquid or solid matrix. These small air bubbles are typically enclosed by thin liquid films, and the protein's foam capacity quantifies its effectiveness in generating and stabilizing this foam structure. Proteins, as surface-active agents, can play a crucial role in forming and stabilizing emulsions. They achieve this by creating electrostatic repulsion on the surface of oil droplets, as described in Kaushal et al., (2012). This electrostatic repulsion helps to prevent the coalescence or aggregation of oil droplets in the emulsion, thereby contributing to the stability of the emulsion. Kheto et al. (2023) reported an increase in the foaming and emulsification ability of plasma-treated guar seed powder. Furthermore, the Emulsifying Capacity (EC) and Foaming Capacity (FC) of the cold plasma (CP)-treated pearl millet flours were higher. This increase in EC and FC can be attributed to the heightened

Table 2
Effect of plasma on rheological properties of different foods.

Food Material	Parameters analyzed	Source of plasma discharge	Voltage/power applied and time	Key outcomes
Rice starch	Viscosity Temperature vs Storage modulus and loss modulus	Bell jar type	40 W – 5, 10 min 60 W – 5, 10 min	Peak viscosity Increase @ 40 W decrease @ 60 WIncrease in G' & G" significantly at three different temperatures stages (Thirumdas et al., 2017)
Corn starch	Viscosity	Dielectric barrier discharge	75 W – 1, 5, 10 min	Decrease in viscosity (Bie et al., 2016)
Wheat flour (Strong) Wheat flour	Storage modulus Loss modulus Viscosity	Dielectric barrier discharge Dielectric barrier discharge	60 kV – 5, 10 min 70 kV – 5, 10 min 80 kV – 5, 10, 20, 30 min	G' and G" were increased with rise in voltage and duration timeG' greater than G" for all treated samples (Misra et al., 2015) Increased peak viscosity with increasing voltage (Chaple et al., 2020)
Pearl millet flour	Viscosity	Atmospheric pressure jet	40 kV – 5, 10, & 15 min 45 kV – 5, 10, & 15 min	Increase of trough, peak viscosity [29]
Little millet flour	Viscosity	Multi pin electric discharge	13 W – 10, 20, 30 min 24 W – 10, 20, 30 min	Viscosity unchanged with treatment @ 30 °C Increased viscosity at 90 °C (Jaddu, Pradhan, et al., 2022)
Quinoa flour	Frequency vs Storage modulus and loss modulus	Dielectric barrier discharge	50 kV – 5, 10 min 60 kV – 5, 10 min	Decrease of G' & G* (Zare et al., 2022)
Gum arabic	Linear viscoelastic region (LVE) Frequency vs Storage modulus and loss modulus Temperature vs Storage modulus and loss modulus	Dielectric barrier discharge	17.5 W – 20, 40 60 min	Plasma has no effect on samples behaved like a liquid in LVE region G' increased @ 20 min, decreased @ 40, 60 min over frequency range G' descended till 55 °C, ascended to 85 °C, increase in holding, slow increase during cooling (Amirabadi et al., 2021)
Xanthan gum	Temperature vs Storage modulus and loss modulus	Surface barrier discharge	3.5 kV – 20, 30 min	Increase in viscosity of treated samples while heating and cooling (Misra et al., 2018)
High methoxyl apple pectin	Frequency vs Storage modulus and loss modulus	Pin to plate electric discharge	190 V, 210 V, 230 V – 3, 6, 9, 12, 15 min	G' and G" were decreased except 190 V 9 min over increase in frequency (Basak & Annapure, 2022)
Locust bean gum	Frequency vs Storage modulus and loss modulus Temperature vs Storage modulus and loss modulus	Multipin electric discharge	30 kV for 10, 20 & 30 min	G' and G" were higher in treated samples compared to control in frequency sweep.G' was decreased initially with increase in temperature and later increased and same increment pattern was continued in holding and cooling phases. (Jaddu et al., 2024)
Kodo millet Starch	Frequency vs Storage modulus and loss modulus	Multipin electric discharge	10 kV – 10, 20 & 30 min 20 kV – 10, 20 & 30 min 30 kV – 10, 20 & 30 min	Both G' and G" increased with plasma treatment. (Sonkar et al., 2023)

surface hydrophobicity resulting from the exposure of hydrophobic protein groups. Additionally, the formation of clumps between amino acid chains due to chain oxidation may be another contributing factor, as noted by Mollakhalili-Meybodi et al., (2021). Moreover, it is possible that extended treatment duration led to an enhancement in surface elasticity. This could be attributed to the weakening of intermolecular interaction bonds, the reduction of sulfhydryl groups, and the exposure of internal hydrophobic residues, all of which can contribute to the improvement of Emulsifying Capacity (EC) and Foaming Capacity (FC) as noted in studies by Kopuk et al., (2022), Sruthi et al. (2022), and Basak and Annapure (2022).

3. Plasma effect on rheological properties of foods

In this section, an exploration of amplitude sweep, frequency sweep, flow curve, and temperature sweep analyses were undertaken on a variety of food samples. The outcomes of these investigations, gleaned from diverse studies, are meticulously summarized and showcased in Table 2 for comprehensive reference.

3.1. Amplitude sweep

Amplitude sweep tests are conducted to differentiate between two regions, namely the linear viscoelastic region (LVE) and the nonlinear viscoelastic region, in most dispersions. This type of testing helps determine the range of strain amplitudes within which a material exhibits linear behavior, providing valuable insights into its viscoelastic properties. In the linear viscoelastic region (LVE), the storage modulus (G'), loss modulus (G"), and loss factor (tan δ) exhibit a constant and parallel trend. If either the storage modulus or the loss modulus starts to decrease, it signifies the entry into the non-linear viscoelastic region, where the material's response to stress is no longer linear and predictable. This transition is an important consideration in the study of material properties and behavior. Strain amplitude was considered with in the LVE for frequency sweep and temperature sweep. G' tends to decrease with high shear rates were observed in treated gum arabic (GA) samples. G" was greater than G' for treated GA and high methoxyl apple pectin samples in the LVE regions was observed (Amirabadi et al., 2021; Basak & Annapure, 2022). The results showed that GA and high methoxyl apple pectin samples behaved as liquid in nature.

3.2. Frequency sweep

Frequency sweep test reveals the variation in elastic and viscous nature of material at constant shear rates. It is also useful test to compare the changes in treatments of viscoelasticity of different foods (Amirabadi et al., 2021). Data obtained from measurements of G' and G" for various materials can be categorized into three distinct groups based on their rheological behavior. In materials exhibiting a gel-like nature, the storage modulus (G') is higher than the loss modulus (G"), and no crossover occurs between the two moduli. This behavior indicates that the material has a solid-like or gel-like structure, where it primarily stores energy (G') rather than dissipating it (G"). For materials resembling concentrated solutions, the loss modulus (G") becomes greater than the storage modulus (G') but only at a relatively lower frequency. There is a crossover point in the frequency sweep test, which typically occurs in the middle of the range. At this crossover frequency, G' is still higher than G". This behavior suggests that the material has characteristics of both a liquid and a solid, often seen in concentrated or semi-solid solutions. When materials behave like diluted solutions, the loss modulus (G") surpasses the storage modulus (G') and there is no intersection or crossover between the two moduli. This indicates that the material predominantly behaves as a liquid and is more viscous than elastic. In such cases, the material lacks the solid-like characteristics observed in gel-like or concentrated solutions (Mirarab Razi et al., 2018). Both the storage modulus (G') and the loss modulus (G") for the treated gum arabic (GA) samples increased across the frequency range with shorter treatment durations. Increase in storage modulus was also observed in plasma treated kodo millet starch (Sonkar et al., 2023). This increase could be attributed to strong intermolecular interactions induced by the plasma species. The loss tangent (tan δ) (G"/G') represents the ratio of the material's viscous and elastic responses during testing. In the case of both the treated strong and weak flours, there was not a significant variation in tan δ. This observation can likely be attributed to the prevailing elastic characteristics of the dough. Variations in viscoelasticity have previously been linked to the glutenin fraction, as indicated by Xu, Bietz, and Carriere (2007). Treatments involving Atmospheric Cold Plasma (ACP) have the potential to alter the protein structure, leading to discernible differences in the material's rheological properties (Misra et al., 2015). The loss tangent exhibited a decrease when the treatment times were shorter and an increase when the treatment times were longer. This trend suggests that the gum dispersions exhibited their highest structural strength in the treated samples, coinciding with an augmentation of their elastic properties.

3.3. Flow curve

Flow curves help characterize the intrinsic properties of materials, such as viscosity, shear rate dependency, and flow behavior. These properties are critical for understanding how materials will behave in various food applications. Various models were applied to determine the exact flow behaviour index and consistency index of material. The increase in apparent viscosity of gum arabic solutions following plasma treatment was observed across the applied frequency range. This phenomenon could be attributed to the heightened hydrophobic nature acquired by gum solutions after undergoing cold plasma treatment (Amirabadi et al., 2021). The power law model provided the best fit ($R^2 > 0.999$) for the cold plasma treated gum arabic dispersions. The same model also exhibited a good fit for cold plasma-treated pearl millet flour, with an $R^2 > 0.98$ (Sarkar et al., 2023). The consistency index is a rheological parameter used to describe the flow behavior of materials, especially fluids and gels. It quantifies how a material's viscosity changes with increasing shear rate or stress. The consistency index for plasma-treated samples, such as gum arabic, pearl millet, and high methoxy pectin, exhibited a significant increase. This increase caused by cross-linking of polymer chains, the formation of new chemical bonds, or changes in the molecular structure. These chemical alterations can lead to increased molecular interactions, making the material more viscous or resistant to flow.

3.4. Temperature sweep

Temperature sweeps are valuable because they provide insights into how materials respond to varying thermal conditions. In the case of plasma-treated xanthan gum samples, there was an observed increase in viscosity was observed across three temperature stages (heating, holding, and cooling) spanning from 20 °C to 60 °C. The storage modulus (G') exhibited a consistent increase with treatment at all three temperature stages, while viscosity showed only minor changes. These effects were attributed to enhanced molecular interactions and a heightened degree of polymerization resulting from the interaction between plasma reactive species and the molecular components of xanthan gum (Misra et al., 2018).

Contrastingly, the storage modulus (G') exhibited a decrease up to 55 °C, followed by a subsequent increase up to 85 °C in plasma treated gum arabic. This increase in G' persisted throughout the holding and cooling phases (Amirabadi et al., 2021). Similar pattern was observed in locust bean gum after plasma treatment (Jaddu et al., 2024). The reduction in the storage modulus indicated the dissipation of energy and the breakage of intermolecular bonds, resulting in reduced energy required for the sample to flow. During holding stage, there was a noticeable increase in the G' value across all dispersions, attributed to the development of hydrophobic bonds. During cooling stage G' increment continued might be due to changes associated with entropy reduction and the formation of hydrogen bonds.

3.5. Viscosity

Viscosity is a crucial parameter for a wide range of food products, including soups, sauces, and concentrated items. It plays a key role in determining the texture, mouthfeel, and overall quality of these food products. In certain studies, viscosity measurements were conducted at two distinct temperatures, typically at 30 °C and 90 °C. This analysis encompassed a variety of flours and starches, including wheat flour, pearl millet flour, little millet flour, and rice starch. These studies revealed that improvement of viscous nature to the material when exposes to plasma treatment (Chaple et al., 2020; Jaddu, Pradhan, et al., 2022; Lokeswari et al., 2021; Thirumdas, Trimukhe, et al., 2017). Rise in viscosity in a starch-based system can result from a combination of factors, including the swelling power of starch granules, the presence of damaged starch granules, the leaching of amylose into the liquid phase, and the hydrolysis of starch molecules. When starch granules swell and absorb water, amylose molecules can leach out into the surrounding liquid. This can increase the concentration of amylose in the liquid phase, potentially leading to higher viscosity. In contrast, Okyere et al. (2019) documented significant decreases in both setback and final viscosities in cereal and tuber waxy starches after undergoing plasma treatment. Moreover, the treatment enhanced the resistance to retrogradation for all three waxy starches, a favorable result when aiming to prevent staling. These factors can collectively contribute to the thickening or gelling, thinning of starch-containing solutions or foods.

4. Plasma effect on nutritional properties of foods

Generally cold plasma have no or little changes in nutritional properties of foods due to non-thermal in nature of plasma (Shashi K. Pankaj et al., 2018). Impact of cold plasma on nutritional profile of some food materials were compiled in Table 3. Several researchers have reported that reduction in moisture content in most of foods with increase in voltage and exposure time. This might due to the formation of free oxygen radicals resulting from the decomposition of water (H_2O) molecules during plasma treatment. Plasma can generate highly reactive species, including free radicals, which can participate in chemical

Table 3
Effect of plasma on bio active and nutritional properties of different foods.

Food Material	Parameters analyzed	Source of plasma discharge	Voltage/power applied and time	Key outcomes
Brown rice	Moisture, protein fat, CHO, ash	Bell jar type	40 W – 5, 10 min 50 W – 5, 10 min	Decrease in moisture Negligible effect on fat, protein, ashNo effect on CHO (Thirumdas et al., 2016)
Long grain brown rice	Moisture	Dielectric barrier discharge (Vacuum system)	1 – 3 V 30 min	Decrease in moisture with plasma treatment (Chen, 2014)
Pearl millet flour	Moisture, protein fat, fiber	Atmospheric pressure jet	40 kV – 5, 10, & 15 min 45 kV – 5, 10, & 15 min	Reduction of moisture Decrease in fat initially later increased with treatment time No effect on proteinDecrease in fiber (Lokeswari et al., 2021)
Pearl millet flour	Moisture, protein fat, CHO TPC, TFC	Multi pin electric discharge	20 kV – 10, 20 min 25 kV – 10, 20 min 30 kV – 10, 20 min	Decrease in moisture and CHO Increase in fat, protein (Sarkar et al., 2023)
Xanthan gum	Moisture, protein fat, CHO, ash	Bell jar type	50 kV – 15, 20 min 60 kV – 15, 20 min	Decrease in moisture No effect on proteinfat, CHO, ash (Bulbul et al., 2019)
Guar seed flour	TPC, TFC	Multi pin electric discharge	10 kV – 5, 10, 15, 20 min 20 kV – 5, 10, 15, 20 min	Less voltage and minimum time enhanced the TPC and at higher voltages TPC started declining Maximum reduction of TFC was noticed at 20 kV 20 min (Kheto et al., 2023)

reactions, including the breakdown of water into oxygen radicals (O·) and hydrogen radicals (H·) (Thirumdas, Saragapani, et al., 2016; Wongsagonsup et al., 2014). Fat content increased with plasma treatment due to lipid oxidation caused by formation of secondary products or derivatives generated from the reactive species such as superoxide (O_2·) and hydroxyl (OH·) radicals (Lokeswari et al., 2021; Sarangapani et al., 2015). The decrease in fiber content in pearl millet following plasma treatment might be attributed to the production of high-intensity electrons during the plasma generation process. Most findings revealed that protein and carbohydrate (CHO) contents of plasma treated foods were no or minimal effects (Bulbul et al., 2019; Lokeswari et al., 2021; Thirumdas, Saragapani, et al., 2016). On contrary increase in protein content of pearl millet was caused by direct effect of OH radicals on the proteinaceous compounds in turn change the final protein content (Sarkar et al., 2023). The reduction in carbohydrate (CHO) and protein content of guar seeds could potentially be attributed to molecular oxidation. This oxidative process may have caused the breakdown of polysaccharide chains, leading to the formation of formic acid, ultimately resulting in decreased carbohydrate content. Additionally, the oxidation process might have affected the protein content as well, leading to its decrease. The increase in the fat content of guar seeds following plasma treatment could be attributed to lipid oxidation. This process might have led to the production of short-chain fatty acids, facilitated by the maximum release rate of lipids from the cell matrix (Kheto et al., 2023). Color is one of most important quality parameter for evaluating quality of any food product. It plays a significant role in consumer perception and acceptance of food. Table 4 presents the color parameters for a range of food materials subjected to plasma treatment. No significant differences were observed in the color values L*, a*, and b* for gum arabic, pearl millet flour, and little millet flour (Amirabadi et al., 2020; Jaddu, Pradhan, et al., 2022; Lokeswari et al., 2021). The increase in the L* value is likely attributable to the degradation of conjugated double bonds within carotenoid pigments by ozone. Carotenoids are responsible for the pale yellow color that can be detected in flour, and their degradation can result in a lighter appearance, as indicated by the increased L* value (Chaple et al., 2020). Whiteness index (WI) was deciding factor for industrial usage of food substances. WI of xanthan gum was drastically increased with plasma treatment (from 76 to 87 %) and minimum WI used for industrial applications were around 75 % (Misra et al., 2018). An enhancement in whiteness index (WI) was also observed in treated brown rice (Thirumdas, Saragapani, et al., 2016). Furthermore, there are additional factors that can contribute to the alteration in the color of starch due to plasma treatment. These factors include oxidation, the Maillard reaction, and structural modifications. Cold plasma, by its nature, generates reactive species like ozone, oxygen radicals, and UV radiation. These highly reactive species can

Table 4
Effect of plasma on color parameters of different foods.

Food Material	Parameters analyzed	Source of plasma discharge	Voltage/power applied and time	Key outcomes
Brown rice	L*, a*, b*, WI	Bell jar type	40 W – 5, 10 min 50 W – 5, 10 min	Enhancement of whiteness valueNo significant changes in L*, a*, b* values (Thirumdas et al., 2016)
Wheat flour	L*, a*, b*, WI	Dielectric barrier discharge	80 kV – 5, 10, 20, 30 min	Increase in L*, whiteness indexDecrease in a*, b* (Chaple et al., 2020)
Pearl millet flour	L*, a*, b*, ΔE, ΔC	Atmospheric pressure jet	40 kV – 5, 10, & 15 min 45 kV – 5, 10, & 15 min	Color intensity increasedMinimal changes in L*, a*, b* values (Lokeswari et al., 2021)
Pearl millet flour	L*, a*, b*, ΔE	Multi pin electric discharge	20 kV – 10, 20 min 25 kV – 10, 20 min 30 kV – 10, 20 min	Increase in L*, ΔEDecrease in a*, b* (Sarkar et al., 2023)
Little millet flour	L*, a*, b*, ΔE, ΔC	Multi pin electric discharge	13 W – 10, 20, 30 min 24 W – 10, 20, 30 min	L* increased for 10 min and 20, 30 min decreased vice versa for a*, b*Decrease in color intensity and Chroma (Jaddu, Pradhan, et al., 2022)
Xanthan gum	L*, a*, b*, WI, ΔE	Surface barrier discharge	3.5 kV – 20, 30 min	Whiteness index improvedSignificant color difference (Misra et al., 2018)
Xanthan gum	L*, a*, b*	Bell jar type	50 kV – 15, 20 min 60 kV – 15, 20 min	Slight increase in yellownessIncrease in color intensity (Bulbul et al., 2019)
Gum arabic	L*, a*, b*, ΔE	Dielectric barrier discharge	17.5 W – 20, 40 60 min	No notable changes of L*, decrease in a*, increase in b* Significant color difference (Amirabadi et al., 2020)

interact with starch molecules, ultimately leading to oxidation. This oxidative process can bring about changes in the chemical composition of starch, resulting in observable shifts in color. For instance, the formation of carbonyl groups during oxidation can induce a browning or yellowing effect in the starch.

5. Bioactive compounds

Bioactive compounds, found in small quantities in foods like whole grains, fruits, and vegetables, offer both nutritional value and health advantages. These compounds, which include vitamins, phytochemicals, and phenolic compounds like flavonoids and carotenoids, have therapeutic potential. They can impact energy intake, reduce inflammation, oxidative stress, and the risk of various diseases, including cancer, Alzheimer's, heart disease, and diabetes (Taş and Gökmen, 2015). Bioactive compounds can modulate metabolic processes through activities like receptor inhibition, antioxidant effects, gene expression regulation, and enzyme modulation, promoting overall health (Siriwardhana et al., 2013). The effect of plasma on bio active compounds present in flours was reported in Table 4.

5.1. Total phenolic content (TPC)

Phenolic compounds are a diverse group of compounds characterized by aromatic rings with hydroxyl groups and various substituents. There are approximately 8000 naturally occurring plant phenolic compounds, with about half of this number belonging to the flavonoid subgroup. Phenolics exhibit a diverse range of biochemical activities, including antioxidant, antimutagenic, anticarcinogenic properties, and the ability to modify gene expression (Zhang et al., 2022). Phenolics represent the largest group of phytochemicals and are responsible for the majority of antioxidant activity in plants and plant-derived products.

A notable increase in total flavonoid content (TFC) was observed in plasma-treated Lotus petal powder (CP-LPP). This rise in flavonoid content in CP-LPP can be ascribed to the release of its components, likely due to modifications on the powder's surface. It has been reported that flavonoid compounds are more readily released with lower energy expenditure from the bound membranes compared to polyphenols (Dakshayani et al., 2021). Cold plasma treatment significantly affected the bioactive compounds in guar seed powder samples, with the applied voltage playing a crucial role. Notably, the highest reduction in Total Phenolic Content (TPC) was observed in samples treated with 20 kV for 20 min, with a decrease of 17.56 %. Likewise, TPC of pearl millet flour gradually decreased with higher applied voltage or longer treatment duration. Conversely, low-intensity plasma treatment, such as 10 kV for 10 min, increased TPC by 8.9 % compared to the control (Kheto et al., 2023).

Plasma treatment at higher levels may accelerate oxidative reactions and degrade phenolic compounds by breaking benzene rings and aliphatic chains (Sruthi et al., 2022; Ali et al., 2021). On the other hand, the increase in TPC could be attributed to the release of bound phenols from the cell matrix. Furthermore, the decrease in phenolic compounds may contribute to the formation of ozone and other reactive species during dissociation processes. This dissociation occurs when individual oxygen atoms combine with oxygen molecules to create ozone.

Conversely, when molecular ozone reacts with the aromatic rings of phenolic compounds, it can lead to the generation of aliphatic molecules, including hydroxylated and quinone compounds. This reaction can ultimately result in the breakdown or degradation of phenolic compounds.

5.2. Total flavonoid content (TFC)

Flavonoids represent the largest group of naturally occurring phenolic compounds, present in various parts of plants both in free forms and as glycosides. They possess a wide range of biological activities, including antimicrobial, mitochondrial adhesion inhibition, antiulcer, antiarthritic, antiangiogenic, anticancer, and protein kinase inhibition, among others (Zhang et al., 2022).

Flavonoids are particularly valuable for their antioxidant properties, offering protection against cardiovascular diseases, certain types of cancer, and age-related cellular degeneration. Their polyphenolic nature allows them to scavenge harmful free radicals, such as superoxide and hydroxyl radicals, contributing to their health benefits.

Maximum reduction in Total Flavonoid Content (TFC), specifically a reduction of 20.58 %, was observed in the Guar seed flour treated with 20 kV for 20 min. However, the higher TFC found in the cold plasma-treated Guar seed flour (GSF) samples may be attributed to the ease of accessing bound flavonoids. On the contrary, the increased presence of reactive species induced oxidative degradation of flavonoid compounds, converting them into lower molecular weight compounds, which subsequently led to a reduction in TFC (S. K. Pankaj et al., 2017; Sruthi et al., 2022). Similarly, decrease in TFC was observed in plasma treated pearl millet flour (Sarkar et al., 2023).

6. Plasma effect on anti-nutritional properties of foods

The anti-nutritional factors in plants, such as tannins, saponins, and phytic acid, are developed as defense mechanisms but can have adverse effects on nutrient bioavailability and protein digestibility when present in excessive amounts in the diet. Balancing dietary intake and employing appropriate food processing methods can help mitigate these effects and ensure adequate nutrient absorption. These anti-nutritional factors bind to essential minerals such as calcium, magnesium, zinc, and iron, forming insoluble complexes that the body cannot absorb effectively. They can also bind to proteins and interfere with the enzymes responsible for breaking down proteins during digestion. This interference leads to reduced protein digestion and absorption in the gastrointestinal tract. Finally, the presence of anti-nutritional factors in excess can indeed hinder the absorption of essential minerals and the digestibility of proteins in the human diet, potentially leading to nutritional deficiencies and reduced nutrient utilization (Kheto et al., 2023). Table 5 provides a comprehensive overview of the anti-nutritional factors found in various foods and their corresponding plasma effects. The subsequent section delves into a detailed discussion of these findings, offering a more in-depth understanding of the information presented in the table.

6.1. Tannin

Tannins and free phenolics are antinutrients found in certain foods such as pomegranate fruits, barks, and leaves, cocoa beans, berry fruits, and drinks (tea, beer, and wine). These are also found in grains such as barley, sorghum, and millets (Samtiya et al., 2020; Suhag et al., 2021). These substances are unsuitable for human consumption owing to their adverse effects. Tannins impede the digestion of proteins, and phenolic compounds diminish the digestibility of proteins and carbohydrates, along with reducing the bioavailability of essential vitamins such as B_{12} and minerals. Additionally, they exert inhibitory effects on key digestive enzymes including trypsin, chymotrypsin, lipase, and α-amylase. It's noteworthy that tannins exist in two primary forms: condensed and hydrolysable. Hydrolysable tannins can be digested, potentially leading to toxic substances, while condensed tannins are nonhydrolysable and remain undigested during the digestive process. Cold plasma treatment decreased tannin content in pearl millet (Sarkar et al., 2023). Reactive oxygen species (ROS) may instigate glycosidic linkage degradation, resulting in a reduction of tannin concentration. Utilizing cold plasma treatment accelerates the oxidation rate of polyphenols, leading to their conversion into simpler molecules. These simpler molecules can potentially form intricate compounds with macromolecules, consequently contributing to the observed reduction in tannin content within guar seeds (Kheto et al., 2023).

Table 5
Effect of plasma on anti-nutritional properties.

Parameters analyzed	Food Material	Source of plasma discharge	Voltage/power applied and time	Key outcomes
Tannin	Pearl millet	Multipin plasma reactor	20 kV – 10, 20 min 25 kV – 10, 20 min 30 kV – 10, 20 min	Tannin content decreased with treatment time (Sarkar et al., 2023)
Trypsin inhibitor activity	Mung bean	Bell jar plasma reactor	40 W – 10, 15, 20 min 60 W – 10, 15, 20 min	Trypsin inhibitor activity decreased with treatment power and time (Sadhu et al., 2017)
	Soymilk	Dielectric barrier discharge	2.9 W – 3, 9, 15, 21, 27 min 33.1 W – 3, 9, 15, 21, 27 min 73.6 W – 3, 9, 15, 21, 27 min 123.7 W – 3, 9, 15, 21, 27 min	TIA reduced with power and time, the highest reduction was at 51.4 W for 27 min (Li et al., 2017)
	Shrimp	Dielectric barrier discharge	10 kV – 1, 2, 3, & 4 min 20 kV – 1, 2, 3, & 4 min 30 kV – 1, 2, 3, & 4 min 40 kV – 1, 2, 3, & 4 min 50 kV – 1, 2, 3, & 4 min	Trypsin activity decreased with treatment time and voltage (Tang et al., 2022)
	Soybean	Dielectric barrier discharge	33.8 kV – 1, 3, 5 min	Decreased with treatment time (Xu et al., 2022)
Phytic acid	Pearl millet	Multipin electric discharge	20 kV – 10, 20 min 25 kV – 10, 20 min 30 kV – 10, 20 min	Decreased with time and power (Sarkar et al., 2023)
	Mung bean	Bell jar type	40 W – 10, 15, 20 min 60 W – 10, 15, 20 min	Decreased with treatment power and soaking time (Sadhu et al., 2017)
	Brown rice	Dielectric barrier discharge (Vacuum system)	400 W – 5 min	Decreased with treatment(Li et al., 2022)
Saponin	Oat	Dielectric barrier discharge	51.7 W – 6 min/day, 6 min for 2 days, 6 min for 3 days	Different saponin found in oat, Saponinn content were decreased till treated with 3 days than increased, Opposite trend was observed for Avenacoside A and B (Lee et al., 2022)

6.2. Saponin

Saponin contains steroidal or triterpene glycosides present in heterogeneous group and is basically attached to glycosyl bonds at C-3 and C-17 (through C-28) points via covalent bound. Saponins may be found in a wide variety of plants used by humans, including legumes (soy, peas, and beans), root crops (potato, yam, asparagus, and allium), oats, sugar beet, tea, and many medicinal herbs such as ginseng. Saponins may reduce protein digestibility owing to informational changes in the protein and coverage of the protein's target residues for digesting enzymes (Suhag et al., 2021). The saponin content of legumes ranges from 0.5 % to 5 % dry weight (Bora, 2014). Whereas, avenacosides and avensides, are two different types of saponin that are present in oats. Plasma treatment acts differently on different types of saponin. The saponin content of oat with growing stages was investigated by plasma treatment for 6 min/day for different days. On one side avenacoside A and B increased for 1 day and 2 days treatment; however it decreases for 3 days treatment. On the other side, Isovitexin-2″-o-arabinoside and Isoswertisin-2″-orhamnoside decreased for 1 day and 2 days treatment, whereas increased for 3 days treatment. However, accumulated saponin content showed subtle changes from the control sample (Lee et al., 2022). The saponin content in plasma treated guar seeds were decreased might be due to the striking of reactive oxygen and nitrogen species breakdown the glycosidic bonds.

6.3. Trypsin inhibitor

Trypsin inhibitors (TIs) are proteins or compounds that interfere with the activity of the enzyme trypsin. Trypsin is a digestive enzyme produced by the pancreas and is crucial for the breakdown of dietary proteins in the small intestine. When trypsin inhibitors are present in the diet, they can inhibit the activity of trypsin, thereby interfering with protein digestion. This can reduce the efficiency of protein digestion in the small intestine, potentially leading to some discomfort, such as flatulence or indigestion, in individuals who consume large amounts of foods containing high levels of trypsin inhibitors. However, this is usually not a significant health concern for most people (Suhag et al., 2021). Rye, triticale, and barley have higher concentrations of protease (trypsin) inhibitor activity in comparison to several other cereal grains (Bora, 2014). The decrease in TI after plasma treatment of mung bean was observed (Sadhu et al., 2017). The plasma treatment of seeds holds the potential to decrease the levels of trypsin inhibitors (TIs) by instigating chemical and structural alterations on the seed surface, which could impact the stability and activity of TIs. This reduction in TIs can contribute to improved protein digestibility and may have implications for various food applications. Rise in the enzyme activity of protease, which could improve the breakdown of trypsin inhibitors even more. In soybeans, plasma treatment was observed to reduce trypsin inhibitor levels. This reduction is primarily attributed to the action of active particles that impart energy to protein surfaces, leading to bombardment and potentially facilitating the breakdown of chemical bonds. Additionally, free radicals generated during this process create active sites on the protein surface and may weaken chemical bonds, ultimately causing protein disintegration (Xu et al., 2022).

6.4. Phytic acid

Phytates, also known as phytic acid or myoinositol hexaphosphate, are compounds that store 1–5 % of phosphorous by weight in cereals, nuts, and legumes. Additionally, 50–85 % of phosphorous is found externally in plants. Phytic acid is present in a crystalline globoid form inside protein bodies in the cotyledon of oilseeds and legumes, as well as in the bran portion of cereals. As grains grow, their phytic acid concentration rises, making for 60–90 % of the total phosphorus in dormant grains (Kumar et al., 2010). Negatively charged phytic acid often forms complexes with positively charged metal ions, such as iron, zinc, calcium, and magnesium, lowering their bioavailability by lowering absorption rates (Samtiya et al., 2020). Phytates have the ability to form chelates with divalent and trivalent metal ions, including Cd, Mg, Zn, and Fe. These chelated compounds are poorly soluble and are not absorbed effectively from the gastrointestinal tract. This reduced absorption leads to decreased bioavailability of these essential minerals, making phytates an antinutritive agent. Many researchers proposed that, if the ratio between phytic acid and Fe/Ca/Zn was more than 1:1, 0.17:1, and 10:1, then the bioavailability of these minerals substantially decreased (López-Moreno et al., 2022). Researchers reported that cold plasma decreased phytic acid content of pearl millet and mung bean significantly (Sadhu et al., 2017; Sarkar et al., 2023). Since free radicals may break down the phytate ring, they may have contributed to the decline in phytic acid. In addition, increased phytase enzyme activity causes the phytic acid content to drop, which could enhance mineral bioavailability (Sadhu et al., 2017). Some researchers also concur with the finding with brown rice (Li et al., 2022).

7. Challenges and future perspective

Despite of having many advantages of cold plasma, there are few limitations such as penetration depth of plasma reactive species upon treated materials was very less (3 – 5 mm). This shallow penetration may restrict the treatment's effectiveness, particularly for thicker or denser materials. Researchers and engineers are continually working to overcome such limitations to maximize the technology's utility in various applications. Lipid oxidation for some kind of products is not desirable that aggravated by generated reactive species. Operating systems at very high voltage and current levels can indeed be extremely dangerous, and there is a significant risk of fatality if proper safety precautions are not taken. High-voltage and high-current systems can pose electrical shock hazards, which can lead to severe injuries or even death if not handled with care. It's imperative to follow strict safety protocols, use appropriate protective equipment, and undergo proper training when working with such systems to minimize the associated risks and ensure the safety of personnel. One of the major limiting factors in the commercialization of this technology is the high capital investment required. Additionally, scaling up to achieve higher capacities demands a substantial discharge area, which adds significant additional costs. These financial barriers can hinder the widespread adoption of cold plasma technology in various industries. Overcoming these challenges, such as finding cost-effective scaling solutions, will be crucial for its broader implementation. The lack of specific legal requirements for cold plasma technology may indeed be a contributing factor to its limited adoption in industrial applications. Regulatory standards and guidelines are essential for ensuring the safety, quality, and compliance of new technologies, especially in industries where they are applied. The absence of established regulations can create uncertainty and reluctance among potential users and investors. Addressing this gap by developing clear legal frameworks and standards for cold plasma technology could help facilitate its movement into industrial applications and promote its responsible and safe use. The optimization of process conditions, including voltage and treatment time, can vary significantly depending on the intended use, such as microbial reduction and enhancing the functionality of different food products. These optimal conditions are not universally established and may require customization for specific applications. Achieving precise and effective treatment parameters is crucial for the success of cold plasma technology in various industries, and ongoing research and development are needed to establish these conditions for different applications and products.

8. Conclusions

Over the last decade, cold plasma technology has found widespread adoption in various food applications. It offers numerous advantages, including the reduction of microbial contamination, enhancement of properties like hydration, rheology, and emulsification, all while preserving the nutritional content and reducing anti-nutritional properties. This technology has played a pivotal role in elevating the quality and safety of food products. The manuscript effectively explores the mechanisms by which plasma reactive species interact with various food materials such as starches, gums, and flours. It delves into the outcomes of these interactions, providing valuable insights into the application of plasma technology in the food industry. Understanding these mechanisms is essential for harnessing the potential benefits of cold plasma treatment on different food products. Major reactions were disintegration of starch molecules and increase in damaged starch content, denaturation of protein, development of hydrophilic bonds, molecular oxidation, leaching of amylose content by break down of long chain starch granules into simpler sugars. Plasma treatment leads to improvements in hydration properties, including water holding capacity, water binding capacity, and solubility index in these flours. Importantly, the generated plasma does not adversely affect the final quality of the flours, and there is no significant loss of nutrients. This underscores the potential benefits of plasma technology in enhancing the functional properties of food materials without compromising their nutritional value. The bombardment of plasma reactive species can lead to the breakdown of glycosidic bonds, which in turn can reduce the presence of anti-nutritional factors in food materials. This degradation of anti-nutritional factors is an important aspect of how cold plasma technology can enhance the nutritional quality of food products. Plasma treatment increases the viscosity of food ingredients by oxidizing starch and enhancing their swelling capacity. Additionally, it induces a shear-thinning behavior in gum dispersions. These changes can be leveraged in the development of new food products aimed at improving textural and sensory characteristics, showcasing the versatility of plasma technology in food formulation and processing. The enhanced functional and rheological properties achieved through cold plasma treatment of cereal and millet flours can be effectively utilized in the production of various food products, including porridges and bakery items. Moreover, researchers have established optimized treatment conditions for kodo millet and investigated the effects of plasma on a range of other food materials, including wheat flour, rice flour, little millet flour, and pearl millet flour. This research contributes to the broader understanding and potential applications of cold plasma technology in food processing.

CRediT authorship contribution statement

Samuel Jaddu: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Shivani Sonkar:** Writing – original draft, Validation, Software, Formal analysis, Data curation, Conceptualization. **Dibyakanth Seth:** Software, Resources, Project administration, Methodology, Investigation, Formal analysis. **Madhuresh Dwivedi:** Validation, Supervision, Resources, Project administration, Methodology, Data curation. **Rama Chandra Pradhan:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Gulden Goksen:** Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Prakash Kumar Sarangi:** Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Anet Režek Jambrak:** Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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