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REVIEW

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Exploring the impacts of novel cold plasma technology on the volatile profile, flavor, and aroma properties of fruits and vegetables—A review

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Abstract

Cold plasma is a novel nonthermal technology that has recently numerous applications in the food industry. It destroys microorganisms, preserves food, and maintains quality without employing chemical antimicrobial agents. However, food processing by cold plasma (CP) can be associated with food quality challenges, so research on the applications of this technology and its effects on food quality are increasing. This paper reviews the effect of CP on the volatile profile, flavor, and aroma properties of fruits and vegetables. CP induces some chemical modifications in volatile compounds, and these changes vary with the CP operating conditions such as voltage, frequency, and treatment duration parameters and subsequently induces changes in the aroma and flavor of foods. The operating conditions may be properly controlled to avoid any unfavorable effects and provide more accepted food by focusing on the development of favorable flavor and aroma characteristics and reducing the incidence of undesirable ones. Also, more sophisticated techniques for sensory evaluation of processed foods should be developed and commercialized to get standardized outcomes. In conclusion, the data presented in this work highlight the possibility of flavor and aroma modifications and improvement of sensory quality in food products by using CP technology.

KEYWORDS
aroma, cold plasma, flavor, fruits and vegetables, volatile profile

1 | INTRODUCTION

In the last few decades, consumers depend heavily on plant-based foods, namely fruits and vegetables, both as a food and as natural sources of bioactive compounds. This global interest has been increased mainly due to their potential ability as free radical scavengers in addition to their antimicrobial, antiproliferative, and anti-inflammatory activities (Aguiar et al., 2021). In this context, prolonging the shelf life along with preserving or improving the nutritional and sensorial properties are important challenges for the food industry (Jongen, 2002; Soares et al., 2017). Different processing methods are used for this purpose aimed mainly to (1) inactivate harmful microorganisms and enzymes, (2) extend the shelf life, (3) reduce moisture content, and/or (4) soften the outer tissue to remove fruit/vegetable peels (Nayak et al., 2015).

Processing food operations may induce either positive or negative changes in the nutritional and sensorial value of treated foods. Heat processing is one of the most common treatments used in the food industry, but it was reported to induce adverse effects on the nutritional, organoleptic, and physicochemical properties of food products (Soares et al., 2017). Consequently, nonthermal processing methods have been considered as alternative or complementary processes to conventional thermal treatments (Alves Filho et al., 2020)among which are high-pressure processing (Marszałek et al., 2017), ultrasound processing (Adekunte et al., 2010), radiation processing (Tremarin et al., 2017), pulsed electric field (Buckow et al., 2013), and cold plasma (CP) (Kumar et al., 2023).

Recently, CP has become the center of research for food processing and became one among the inevitable and profitable food industry choices due to its short treatment time and minimal thermal effects on food products with potential enzyme inactivation (Misra, 2016), toxin removal (Misra, 2015), food decontamination (Misra et al., 2011), and packaging modification (Mandal et al., 2018; Pankaj et al., 2014). Plasma is the fourth state of matter, and CP has many applications in different industrial sectors; however, recently, there is a great interest and growing research efforts in using the CP technique as an alternative food processing method (Misra, 2016).

Aromas are key components contributing to the flavor of fruits and vegetables, and the flavor composition has been defined as a complex attribute of quality, in which the mix of sugars, acids, and volatiles play a primary role (El Hadi et al., 2013). Fruit aroma is determined by a complex mixture of many volatile compounds including alcohols, aldehydes, and esters (Defilippi et al., 2009; El Hadi et al., 2013). Recently some review articles have been published on the food processing by CP, focusing mainly on the potentials of CP technology for microbial decontamination (Ekezie et al., 2019; Misra & Jo, 2017; Nwabor et al., 2022; Punia Bangar et al., 2022), induced chemical, physical, and physiological quality attributes (Bourke et al., 2018; Chen et al., 2020; Saremnezhad et al., 2021), and changes of proteins (Kopuk et al., 2022; Muhammad et al., 2018; Pankaj et al., 2018; Tolouie et al., 2018), lipids (Gavahian et al., 2018; Pérez-Andrés et al., 2020), vitamins, and polyphenolic compounds (Kumar et al., 2023; Muhammad et al., 2018; Munekata et al., 2020; Pankaj et al., 2018; Saremnezhad et al., 2021; Sruthi et al., 2021) after CP processing. However, a detailed review on the impact of CP treatment on the volatile organic compounds (VOCs), in fruits and vegetables is lacking in the available literature. In this review, we studied in detail and for the first time, the published articles related to the effects of CP on the volatile profile and major volatile classes and compounds of fruits and vegetables and the subsequent changes in the aroma and flavor properties.

2 | PRINCIPLES AND PARAMETERS OF COLD PLASMA

CP treatment is a novel, nonthermal processing technique recently utilized in food sterilization as an alternative to traditional thermal processing techniques for preserving the quality attributes of food. It is an ionized or partially ionized gas composed mainly of chemically reactive species: electrons, atoms, molecules, electrically charged ions, free radicals, photons, and visible light. A variety of gases have been employed for generating plasma: helium, argon, or their combination with oxygen releasing reactive oxygen and nitrogen species together with UV photons, positive and negative ions (Misra, 2016). Plasmas are divided into thermal and nonthermal types, based on their mechanism of generation and the relative temperature between particles. Thermal plasma is achieved by heating gas in sufficiently high temperatures to be ionized, resulting in the thermodynamic temperature equilibrium among all chemical species. The low-temperature plasma is divided into quasi-equilibrium and none-equilibrium plasmas (CP) (Puligundla et al., 2020). Several devices could be used for plasma generation such as corona discharge, glow discharge, dielectric barrier discharge (DBD), and microwave discharge (Niemira, 2014; Sakudo et al., 2020). The corona discharge system can work at the direct current or pulsed voltage mode and is usually created at atmospheric pressure, in which there is no need for complex apparatus or high operating costs (Coutinho et al., 2018). In DBD, there are two electrodes with dielectric covers to generate plasma that operates at frequencies from 0.05 to 500 kHz and gas pressures from 104 to 106 Pa (Sakudo et al., 2020; Zhang et al., 2017). Among the benefits of DBD are the short DBD generation time, a large variety of used gases, and the homogenous discharge. However, it still has limitations for large-scale applications due to the few spaces between the two dielectric plates hindering the exposure of large surface areas and volumes of foods (Herianto et al., 2021; Phan et al., 2017). Glow discharge is a plasma generated at low temperatures and in a large volume by applying direct voltage to low pressure gas with low pressure (Sakudo et al., 2020). Microwave discharges are easy to handle, they are generated under a low gas pressure by a magnetron, and then electrons absorb the microwaves' increasing kinetic energy and ionization reactions (Coutinho et al., 2018; Sakudo et al., 2020; Saremnezhad et al., 2021).

Both, the power or voltage applied across the electrodes and the plasma excitation frequency are among the important parameters that should be considered during processing since they significantly affect the amount of generated reactive species in the plasma and consequently affect the bioactive compounds in processed food. Campelo et al. (2020a) reported that the excitation frequency applied in the DBD plasma induced significant changes in the volatile profile and aroma of camu-camu pulp juice in which the lower excitation frequency (420 Hz) induced a reduction and conversion of camphene, borneol, and α-fenchol into α-pinene and then into α-terpineol, limonene, and α-phellandrene leading to a decrease in the camphoraceous notes (by 27.0%) and an increase in the citrus note (by 10.4%). The contrary was observed at higher excitation frequencies (700 and 960 Hz) (Campelo et al., 2020a). The same study showed a reduction in β-caryophyllene at 420 Hz being converted to α-humulene, α-bulnesene, γ-cadinene, cadina-1(2),4-diene, α-calacorene, and germacrene B, leading to an increase in the woody notes. However, at 700 and 960 Hz woody, terpenic, and spicy notes showed insignificant changes. Interestingly juice processed at the highest excitation frequency (30,000 Hz) followed the same trend as in that of 420 Hz.

Among the other important parameters that could influence the quality of the processed food are the following: feed gas type (noble gases, oxygen, nitrogen, air, or gas mixtures), gas flow rate, and plasma treatment times that could affect the nature of produced reactive species and induce various chemical reactions (Kumar et al., 2023). In this context, Campelo et al. (2020b) reported that short processing time and the low plasma flow rate led to a 9.4% increase in the woody notes and 23.7% reduction in the camphoreous notes of the camu-camu pulp due to the rearrangement and conversion of α-fenchol to camphene. However, increasing both processing time and/or plasma flow rates induced significant loss of woody and citrus notes.

Increasing the exposure time to plasma would give enough time for reactive species to influence the chemical compounds of the food, forming new compounds, or inducing degradation reactions (Kumar et al., 2023). For example, increasing the plasma treatment time of lemon verbena led to a reduction in the content of the essential oil (EO) from 1.2 to 0.9 (% v/w).

3 | THE EFFECT OF COLD PLASMA ON THE VOLATILE PROFILE

Generally, food processing induces chemical reactions between a wide range of metabolites, leading to production of volatile aromatic organic compounds. CP as a method of food decontamination is being used increasingly in the food industry, and together with the impact of this process on microorganisms, the influence on the quality characteristics of fruits and vegetables, including the VOCs profile, is also important. Figure 1 shows the different parameters that could induce changes on the volatile profile of fruits and vegetables upon treatment by CP. Unfortunately, treatment with the use of plasma is associated with the intensification of the fat oxidation process in the raw material, which results in the formation of secondary volatile and nonvolatile compounds such as alcohols, aldehydes, carbonyls, furans, and hydrocarbons (Wojtasik-Kalinowska et al., 2023). Kodama et al. (2014) reported that plasma treatments had a significant effect on citrus EO composition, and limonene, γ-terpinene, and β-pinene in the EO were reduced (Kodama et al., 2014).

In addition, Hertwig et al. (2015) reported that the amount of piperine in CP-treated black pepper was only slightly lower than the amount determined in the untreated one. The results revealed that pepper quality was relatively unaffected by CP treatments (after 15 and 30 min) (Hertwig et al., 2015). Also, Shirani, Shahidi (Shirani et al., 2020) observed C5–C11 aldehydes in plasma-treated almond samples, which are the most common oleic and linoleic acid oxidation products. Hexanal, nonanal, and octane can result in odor that causes an undesirable effect on almond aroma and quality. These compounds further increase during storage and oxidation. Chutia et al. (2020) reported a chemical change of odor in plasma-treated tender coconut water and suggested blending 1% orange juice to mask this flavor. Similar results were found on plasma-treated apple slices by Schnabel et al. (2015). However, the authors concluded that the noticed changes could not be associated with the plasma treatment. The effects of CP treatment on some major VOC classes in different fruits and vegetables are discussed below in details and illustrated in Table 1.

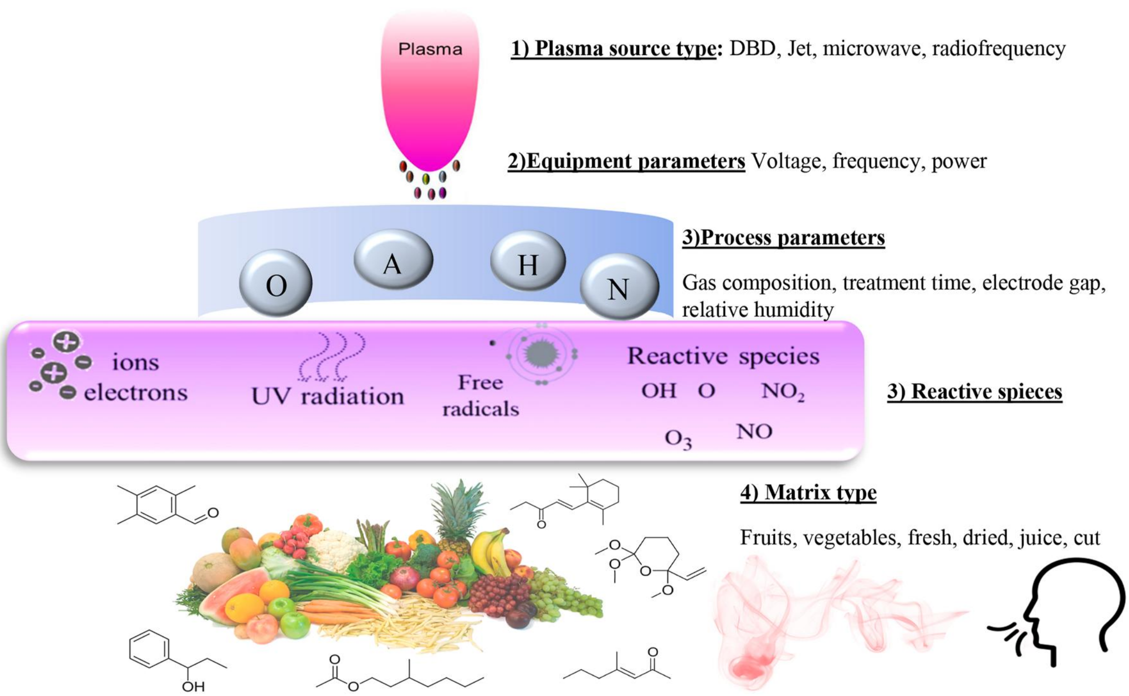

FIGURE 1 Major parameters responsible for volatile profile changes after cold plasma treatment.

TABLE 1 Effect of cold plasma treatment on volatile profile (VOC) of various fruits, vegetables and food products.

			Plasma treatment conditions					
Class	Compounds	Sample	Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
Alcohols	Glycerol	Tomato juice	Electric discharge	10 kV	-	5 min	↑ After plasma treatment	Ma and Lan (2015)
	L-threitol	Tomato juice	Electric discharge	10 kV	-	5 min	Produced by plasma treatment	Ma and Lan (2015)
	1-ethoxy-2-propanol	Tomato juice	Electric discharge	10 kV	-		↑ By 71.8%	Ma and Lan (2015)
	3-methylbutan-1-ol	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000 and 30,000 Hz	5 and 15 min	Nonsignificant change with 200 Hz and significant ↓ with all higher frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge plasma	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
	1-heptanol	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment in all storage days	Zhou et al. (2022)
	1-octen-3-ol	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ By T1: 40 kV-90 s, and disappeared by the other studied treatments (T2: 50 kV-90 s; T3: 40 kV-180 s; T4: 50 kV-180 s)	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	Exhibited first ↓ trends but ↑ afterward at days 6 and 8	Zhou et al. (2022)
	1-hexanol, 2-ethyl-	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment in all storage days	Zhou et al. (2022)
	Phenylethyl alcohol	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↑ In T1: 40 kV-90 s, and disappeared in the other studied treatments (T2: 50 kV-90 s; T3: 40 kV-180 s; T4: 50 kV-180 s)	Liu et al. (2021)
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2 ↓ By PAW-10, PAW-20 Lost By PAW-5	Abouelenein et al. (2021)
	Hex-3-en-1-ol	Camu-camu pulp	DBD plasma	Voltage of a 10 & 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 200 Hz and significant ↓ with all higher frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge plasma	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, PAW-10 ↓ By PAW-5, PAW-20	Abouelenein et al. (2021)
	Hexan-1-ol	Camu-camu pulp	DBD plasma	Voltage of a 10 & 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 200 Hz and significant ↓ with all higher frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge plasma	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
		Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	Benzyl alcohol	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment in all	Zhou et al. (2022)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
							storage days	
	(Z)-2-dodecenol	Fresh-cut cantaloupe	-	40 kV		90 s	↑ In all storage days but significantly ↓ at days 4 and 8	Zhou et al. (2022)
	1-octanol	Fresh-cut cantaloupe	-	40 kV		90 s	Exhibited first ↑ trends up to day 6	Zhou et al. (2022)
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5, PAW-20 ↓ By PAW-2, PAW-10	Abouelenein et al. (2021)
	(Z)-3-nonen-1-ol	Fresh-cut cantaloupe	-	40 kV		90 s	Treatment significantly inhibited the ↓ until day 2 but significantly stimulated the synthesis from 4 to 8 days	Zhou et al. (2022)
	3,6-nonadien-1-ol	Fresh-cut cantaloupe	-	40 kV		90 s	Not detected in treated samples until day 4 but then ↑ at days 4–8	Zhou et al. (2022)
	(E)-2-nonen-1-ol	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment up to day 6 and then ↓ afterward	Zhou et al. (2022)
	1-nonanol	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment at days 0, 4, 6, and 10	Zhou et al. (2022)
	1-undecanol	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment at days 4, 6, and 8	Zhou et al. (2022)
	Dimethylcyclohexanol	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment at days 0, 4, 6, and 10	Zhou et al. (2022)
	n-Heptadecanol-1	Fresh-cut cantaloupe	-	40 kV		90 s	Not detected in almost all treated samples	Zhou et al. (2022)
	Pent-1-en-3-ol	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	Pentan-1-ol	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, PAW-20 Not changed by PAW-10	
	(Z)-2-penten-1-ol	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	Nonan-1-ol	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, PAW-5 ↓ By PAW-10, PAW-20	Abouelenein et al. (2021)
Aldehydes	Furfural	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	trans-2-hexenal	Tomato juice	Electric discharge	10 kV	-	5 min	↑ After plasma treatment	Ma and Lan (2015)
	Hexanal	Tomato juice	Electric discharge	10 kV	-	5 min	↑ By 1.6 times	Ma and Lan (2015)
		Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	Cold plasma significantly inhibited the ↓ until 6 days but boosted the ↓ at 8 and	Zhou et al. (2022)

(Continues)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
							10 days	
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, and PAW-10 ↓ By PAW-20	Abouelenein et al. (2021)
	Heptanal	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	↓ At 0, 4 and 10 days and ↑ at 8 and 10 days compared to the nontreated samples	Zhou et al. (2022)
	Acetal	Tomato juice	Electric discharge	10 kV	-	5 min	↑ After plasma treatment	Ma and Lan (2015)
	Benzaldehyde	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	Significant higher contents in treated samples at days 0, 2, 6, and 10	Zhou et al. (2022)
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	(*E*)-2-hexenal	Fresh-cut cantaloupe	-	40 kV		90 s	Cold plasma significantly inhibited the ↓ until 6 days but boosted the ↓ at days 8 & 10	Zhou et al. (2022)
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2 and AW-5, PAW-10 ↓ By PAW-20	
	(*E*)-2-pentenal	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment at all storage days up to day 10	Zhou et al. (2022)
	Nonanal	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	Generally, ↓ during the storage, with the values ranging from 4.02 to 2.14 µg/kg. Significant higher contents identified in treated samples at days 2-4	Zhou et al. (2022)
	(*E*)-2-octenal	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment up to day 8 and then ↓ at day 10	Zhou et al. (2022)
	2-dodecenal	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment up to day 8 and then ↓ at day 10	Zhou et al. (2022)
	Decanal	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ By T1: 40 kV-90 s; T2: 50 kV-90 s; T4: 50 kV-180 s ↑ By T3: 40 kV-180 s	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	Maintained or ↑ after plasma treatment up to day 8	Zhou et al. (2022)
	2,4-nonadienal	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment up to day 8 then ↓ at day 10	Zhou et al. (2022)
	(*E*)-2-nonenal	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	β-cyclocitral	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment at day 2 storage and then ↓ or even	Zhou et al. (2022)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
							lost with other storage times	
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	4-oxononanal	Fresh-cut cantaloupe	-	40 kV		90 s	Treatment inhibited the ↓ until 6 days but boosted the ↓ at days 8 and 10	Zhou et al. (2022)
	2-methyl propanal	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	2-methyl butanal	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5 ↓ By PAW-2, AW-10, and PAW-20	Abouelenein et al. (2021)
	3-methyl butanal	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5 ↓ By PAW-2, AW-10, and PAW-20	Abouelenein et al. (2021)
	Pentanal	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, and PAW-10 Not changed by PAW-20	Abouelenein et al. (2021)
	Octanal	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	Nonanal	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5 and PAW-20 ↓ By PAW-2 and AW-10	Abouelenein et al. (2021)
	3-furfural	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, PAW-5, and PAW-20 ↓ By PAW-10	Abouelenein et al. (2021)
	Benzene acetaldehyde	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	2-methyl benzaldehyde	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
Ketones	3-octanone	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment at all storage days up to day 10	Zhou et al. (2022)
	Farnesyl acetone	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment at all storage days up to day 10 but not detected at day 8	Zhou et al. (2022)
	Geranyl acetone	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	Produced by only T1: 40 kV-90 s, and T4: 50 kV-180 s treatments	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	Not detected at day 0, but ↑ after plasma treatment up to day 10	Zhou et al. (2022)
		Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, and PAW-10 ↓ By PAW-20	Abouelenein et al. (2021)
	β-ionone	Fresh-cut cantaloupe	-	40 kV		90 s	↓ At day 0, but ↑ afterward up to day 10	Zhou et al. (2022)
		Rocket salad	PAW		5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein

(Continues)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
				9 kV 80.95 ± 33.42 W				et al. (2021)
	2,5-dimethyl-3-hexanone	Rocket-salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5, AW-10, and PAW-20 Lost By PAW-2	Abouelenein et al. (2021)
	3-hydroxybutan-2-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5 ↓ By PAW-2, AW-10, and PAW-20	Abouelenein et al. (2021)
	1-hydroxypropan-2-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5 ↓ By PAW-2, AW-10 and PAW-20	Abouelenein et al. (2021)
	6-methyl-5-hepten-2-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, and PAW-10 ↓ By PAW-20	Abouelenein et al. (2021)
	3-octen-2-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	3,5-octadien-2-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	(3E,5E)-3,5-octandiene-2-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	6-methyl-3,5-heptadien-2-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, and PAW-10 ↓ By PAW-20	Abouelenein et al. (2021)
	β-ionone-5,6-epoxide Norisoprenoid	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	6,10,14-trimethylpentadecan-2-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2 and PAW-5 ↓ By PAW-10 and AW-20	Abouelenein et al. (2021)
	Dihydroactinidiolide Norisoprenoid	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, and PAW-10 ↓ By PAW-20	Abouelenein et al. (2021)
Esters								
		Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	Nonyl chloroformate	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	2-methylpropyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	Significant ↑ after plasma treatment Control samples increased up to the peak value at day 2 and at day 8 in treated ones	Zhou et al. (2022)
	2-methylbutyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment	Zhou et al. (2022)
	Bis(2-ethylhexyl) maleate	Fresh-cut cantaloupe	-	40 kV		90 s	Not detected at day 0 and afterward ↑ after plasma treatment	Zhou et al. (2022)
	Hexyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	Fluctuating changes in control and treated samples, but CP ↑ hexyl acetate production	Zhou et al. (2022)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
							compared to the control	
	Isobutyl nonyl carbonate	Fresh-cut cantaloupe	-	40 kV		90 s	Fluctuating changes in control and samples	Zhou et al. (2022)
	Benzyl dodecanoate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment except for day 6	Zhou et al. (2022)
	Heptyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment	Zhou et al. (2022)
	Ethyl laurate	Tomato juice	Electric discharge	10 kV	-	5 min	Lost by plasma treatment.	Ma and Lan (2015)
	Ethyl butanoate	Camu-camu pulp	DBD plasma	Voltage of a 10 & 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↓ with all frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
	Hydroxymandelic acid ethyl ester	Fresh-cut cantaloupe	-	40 kV		90 s	Nonsignificant differences between treated a control sample	Zhou et al. (2022)
	Benzyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment	Zhou et al. (2022)
	Tetradecadienyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	Not detected in most control and plasma-treated samples	Zhou et al. (2022)
	Phenethyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	Not detected at day 0 and then ↑ afterward up to day 8	Zhou et al. (2022)
	Octyl heptafluorobutyrate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment up to day 6 and then ↓ afterward	Zhou et al. (2022)
	cis-non-3-en-1-yl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment	Zhou et al. (2022)
	cis-6-nonenyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment	Zhou et al. (2022)
	Nonenyl acetate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment	Zhou et al. (2022)
	Pentadecyl hexanoate	Fresh-cut cantaloupe	-	40 kV		90 s	Fluctuating changes in the control and samples	Zhou et al. (2022)
	Butyl butanoate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment	Zhou et al. (2022)
	Heptadecanoic acid heptadecyl ester	Fresh-cut cantaloupe	-	40 kV		90 s	Fluctuating changes in the control and samples	Zhou et al. (2022)
	2-tetradecyl methoxy acetate	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment except for day 8 where it's not detected	Zhou et al. (2022)
	Methyl palmitate	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5 ↓ By PAW-2, AW-10, and PAW-20	Abouelenein et al. (2021)
Terpenes	α-pinene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↑ with 200 Hz, nonsignificant change with 420 Hz, and then significant ↓ with all higher frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)

(Continues)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
		Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	Camphene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↓ with all frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ At lower flow rate 10 mL/min and ↑ at higher flow rate 30 mL/min	Campelo et al. (2020b)
		Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	Lost after plasma treatment at all-time points	Ebadi et al. (2019)
	Camphor	Fresh-cut cantaloupe	-	40 kV		90 s	↑ At day 6 but nonsignificant changes with other time points	Zhou et al. (2022)
	β-pinene	Camu-camu pulp	DBD plasma	Voltage of a 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↑ with all frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
	Sabinene	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↓ After plasma treatment at all-time points	Ebadi et al. (2019)
	Myrcene	Camu-camu pulp	DBD plasma	Voltage of a 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↓ with all frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
	α-phellandrene	Camu-camu pulp	DBD plasma	Voltage of a 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 200 & 580 Hz significant ↑ with 420, 700, and 960 Hz and significant ↓ with higher frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
	Limonene	Camu-camu pulp	DBD plasma	Voltage of a 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 420, 580, and 700 Hz and significant ↑ with 200 & 960 Hz and significant ↓ with higher frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
		Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	1, 8 cineole	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	γ-terpinene	Camu-camu pulp	DBD plasma	Voltage of a 10 and 20 kV	200, 420, 580, 700, 960, 12,000, 30,000 Hz	5 and 15 min	Significant ↑ with all frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ At 10 mL/min and 10 min treatment time ↑ At 20 mL/min and 20,30 min treatment ↑ At 30 mL/min and 10, 20 min treatment	Campelo et al. (2020b)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
							↓ With other conditions	
		Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points but lost at 3 min treatment	Ebadi et al. (2019)
	Terpinolene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↓ with all frequencies except for 960 Hz that showed significant ↑	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
		Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↓ After plasma treatment at all-time points and lost at longest treatment time 5 min	Ebadi et al. (2019)
	Citronellal	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	Neral	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↓ After plasma treatment at all-time points	Ebadi et al. (2019)
	Geranial	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↓ After plasma treatment at all-time points	Ebadi et al. (2019)
	Neryl acetate	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↓ After plasma treatment at all-time points	Ebadi et al. (2019)
	α-fenchol	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↓ with all frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
	Borneol	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↓ with all frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
	Trans-pino carveol	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	Lost after plasma treatment at all-time points	Ebadi et al. (2019)
	Cis- sabinol	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	Lost after plasma treatment at all-time points	Ebadi et al. (2019)
	4-terpineol	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 200 Hz and significant ↓ with all higher frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
	α-terpineol	Camu-camu pulp	DBD plasma	Voltage of a 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 200, 960, and 12,000 Hz and significant ↓ with all other frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
		Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	Nerol	Lemon verbena shrubs	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ after short plasma treatment	Ebadi et al. (2019)

(Continues)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
		(EO)					and then lost with longer treatment times	
	β-caryophyllene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 420 Hz, significant ↑ with 200 and 960 Hz and significant ↓ with other frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↑ After plasma treatment	Campelo et al. (2020b)
	E-caryophyllene	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↓ After plasma treatment at all-time points	Ebadi et al. (2019)
	α-copaene	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↓ After short plasma treatment and then lost with longer treatment times	Ebadi et al. (2019)
	γ-Elemene	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	α-Gurjunene	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	Lost after plasma treatment at all-time points	Ebadi et al. (2019)
	α-humulene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 960 Hz, significant ↑ with all other frequencies except for 700 Hz that showed significant ↓	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
		Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After 3 min treatment and ↓ with other treatments	Ebadi et al. (2019)
	α-bulnesene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↑ with all frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
	γ-cadinene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↑ with 420, 580, 700 and 12,000 and significant ↓ with other frequencies	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
	Cadina-1(2),4-diene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↑ with all other frequencies except for 700 Hz that showed significant ↓	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
	Selina-3,7(11)-diene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 1200 Hz and significant ↑ with 420, 580, 700, and 30,000 Hz except for 200 and 960 Hz that showed significant ↓	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
	α-calacorene	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Nonsignificant change with 1200 Hz, significant ↑ with 420, 580, 700, and 30,000 Hz except for 200 and 960 Hz that showed significant ↓	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
	Germacrene B	Camu-camu pulp	DBD plasma	Voltage of 10 and 20 kV	200, 420, 580, 700, 960, 12,000, and 30,000 Hz	5 and 15 min	Significant ↑ with 420, 580, 700, 12,000, and 30,000 Hz except for 200 and 960 Hz that showed significant ↓	Campelo et al. (2020a)
		Camu-camu pulp	Glow discharge	80 kV	50 kHz	10, 20, and 30 min	↓ After plasma treatment	Campelo et al. (2020b)
	Cubenol	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↓ After plasma treatment	Ebadi et al. (2019)
	Spathulenol	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	Globulol	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	Epi-α-cadinol	Lemon verbena shrubs (EO)	LPCP system	1200 W	2.45 GHz	0, 1, 3, and 5 min	↑ After plasma treatment at all-time points	Ebadi et al. (2019)
	Longicyclene	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	Produced by only T3: 40 kV-180 s; T4: 50 kV-180 s	Liu et al. (2021)
	Longifolene	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	Fluctuating changes in the control and samples	Zhou et al. (2022)
Benzene derivatives	m-xylene	Tomato juice	Electric discharge	10 kV	-	5 min	Produced by plasma treatment	Ma and Lan (2015)
	o-xylene	Tomato juice	Electric discharge	10 kV	-	5 min	Produced by plasma treatment	Ma and Lan (2015)
	3-methyl-4-isopropylphenol	Fresh-cut cantaloupe	-	40 kV		90 s	↑ After plasma treatment at all-time points	Zhou et al. (2022)
	3-*tert*-butylphenol	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	Lost by all studied treatments	Liu et al. (2021)
	Styrene	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
Hydrocarbons	2-ethoxy propane	Tomato juice	Electric discharge plasma	10 kV	-	5 min	↑ After plasma treatment	Ma and Lan (2015)
	2-ethoxy-pentane	Tomato juice	Electric discharge	10 kV	-	5 min	Decreased by plasma treatment	Ma and Lan (2015)
	Dodecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	↑ Or at least not changed after plasma treatment	Zhou et al. (2022)
	Tridecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	Produced by only T4: 50 kV-180 s	Liu et al. (2021)
	Tetradecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ By T1: 40 kV-90 s ↑ By T2: 50 kV-90 s; T3: 40 kV-	Liu et al. (2021)

(Continues)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
							180 s; T4: 50 kV-180 s	
		Fresh-cut cantaloupe	-	40 kV		90 s	↑ Or at least not changed after plasma treatment	Zhou et al. (2022)
	Pentadecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	Lost by all studied treatments	Liu et al. (2021)
	Hexadecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↑ By T2: 50 kV-90 s; T3: 40 kV-180 s ↓ By T1: 40 kV-90 s; T4: 50 kV-180 s	Liu et al. (2021)
	2,3-dimethyldodecane	Fresh-cut cantaloupe	-	40 kV		90 s	↑ Or at least not changed after plasma treatment	Zhou et al. (2022)
	Undecylcyclopentane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ By T1: 40 kV-90 s; T4: 50 kV-180 s ↑ By T2: 50 kV-90 s; T3: 40 kV-180 s; T4: 50 kV-180 s	Liu et al. (2021)
	3-methylheptadecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	5-butylhexadecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	5-methylundecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	Produced by only T3: 40 kV-180 s	Liu et al. (2021)
	7-hexyl-tridecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	Nonylcyclopentane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↑ By T1: 40 kV-90 s; T2: 50 kV-90 s ↓ By T3: 40 kV-180 s; T4: 50 kV-180 s	Liu et al. (2021)
	8-hexylpentadecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	9-methylnonadecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↓ In all studied treatments	Liu et al. (2021)
	10-methylnonadecane	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	Produced by only T3: 40 kV-180 s; T4: 50 kV-180 s	Liu et al. (2021)
	(E,E,E)-2,4,6-octatriene	Fresh-cut cantaloupe	-	40 kV		90 s	↑ Up to day 4 and then not detected afterward	Zhou et al. (2022)
	Undecane	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5, PAW-10, and PAW-20 ↓ By PAW-2	Abouelenein et al. (2021)
Lactone s	γ-Heptalactone	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	Produced by T1: 40 kV-90 s. T2: 50 kV-90 s; and T3: 40 kV-180 s	Liu et al. (2021)
		Fresh-cut cantaloupe	-	40 kV		90 s	↓ At day 0 but ↑ afterward up to day 10	Zhou et al. (2022)
	Dihydroactinidiolide	Fresh-cut cantaloupe	-	40 kV		90 s	Nonsignificant changes up to day 2 and then ↑ afterward	Zhou et al. (2022)
Pyrazines	2,5-dimethylpyrazine	Brown rice	DBD plasma	40 and 50 kV	-	1.5–3 min	↑ By T3: 40 kV-90 s ↓ By T4: 50 kV-180 s Lost by T1: 40 kV-90 s; T2: 50 kV-90 s	Liu et al. (2021)

TABLE 1 (Continued)

Class	Compounds	Sample	Plasma treatment conditions: Plasma source	Power/voltage	Frequency	Exposure time	Findings	Ref.
Sulfur compounds	Methyl disulphide	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5 and PAW-20 ↓ By PAW-2 and PAW-10	Abouelenein et al. (2021)
	Dimethyl sulphide	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	Dimethyl trisulphide	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5 ↓ By PAW-2, PAW-10, and PAW-20	Abouelenein et al. (2021)
	Dihydro-2H-thiopyran-3(4H)-one	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↓ By all treatments	Abouelenein et al. (2021)
	Dimethyl sulfoxide	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	Dimethyl sulfone	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, and PAW-20 ↓ By PAW-10	Abouelenein et al. (2021)
Acids	Acetic acid	Rocket-salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-5, AW-10, and PAW-20 ↓ By PAW-2	Abouelenein et al. (2021)
	Propanoic acid	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	Hexanoic acid	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, AW-5, and PAW-20 ↓ By PAW-10	Abouelenein et al. (2021)
Glucosinolate hydrolysis products	Methyl thiocyanate	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	5-methyl Hexanenitrile	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2 and PAW-10 ↓ By PAW-20. Lost by PAW-5	Abouelenein et al. (2021)
	Heptanonitrile	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	Not changed by PAW-2. ↓ By PAW-10 and PAW-20 Lost By PAW-5	Abouelenein et al. (2021)
	1-butene 4-isothiocyanate	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By all treatments	Abouelenein et al. (2021)
	4-methylthio butanenitrile	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2 and PAW-10 ↓ By PAW-20. Lost by PAW-5	Abouelenein et al. (2021)
	Erucin nitrile	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↓ By all treatments	Abouelenein et al. (2021)
	Erucin	Rocket salad	PAW	9 kV 80.95 ± 33.42 W	5 kHz	2, 5, 10, and 20 min	↑ By PAW-2, PAW-5, and PAW-20 ↓ By PAW-10	Abouelenein et al. (2021)

Note: PAW-2, PAW-5, PAW-10, and PAW-20 refer to rocket samples subjected to plasma activated water (PAW) treatment for 2, 5, 10, and 20 min, respectively.

Abbreviations: DBD, dielectric barrier discharge; EO, essential oil; LPCP, low-pressure cold plasma; PAW, plasma activated water; VOC, volatile organic compound.

3.1 | Alcohols

Alcohols may be formed by the decomposition of fatty acid hydroperoxides or the reduction in aldehydes (Liu et al., 2015). They are used as a defensive mechanism of plants and are often responsible for the "cut grass" aroma found in leafy vegetables (Bell et al., 2017; Ruther & Kleier, 2005). In camu-camu pulp, α-terpineol was increased slightly after DBD plasma application at 200 and 960 Hz. However, a reduction was observed for all other alcoholic compounds (3-methylbutan-1-ol, hexan-1-ol, α-fenchol, borneol, hex-3-en-1-ol, and 4-terpineol). Nonsignificant changes were only observed for 3-methylbutan-1-ol, hex-3-en-1-ol, and hexa-1-ol when DBD plasma was applied at 200 Hz (Campelo et al., 2020a). In this study DBD led to alcohol molecules dehydration, where the 4-terpineol was dehydrated forming the pinene radical, which induced α-phellandrene and myrcene formation. Also, part of the borneol and α-fenchol were dehydrated and hydrogenated to form camphene (Liu et al., 2008). The only alcohol that was little affected was α-terpineol being a more stable molecule. On the other hand, glow discharge plasma induced an increase of alcohols contents in the camu-camu pulp. Furthermore, Ma and Lan (2015) reported production or increment of alcohols such as 1-ethoxy-2-propanol, L-threitol, and glycerol of tomato juice after treatment by CP. Volatile components of tomato juice increased after CP treatment by 71.8% while increased with heat sterilization by 256.4%. CP treatment had no significant effect on the smell and volatile components of tomato juice, but the change of heat sterilization was significantly higher than that of CP treatment (Table 1).

Liu et al. (2021) reported that alcohols and aldehydes were the most abundant classes of aroma compounds in all brown rice samples treated by different conditions of DBD-CP (T1: 40 kV-90 s; T2: 50 kV-90 s; T3: 40 kV-180 s; T4: 50 kV-180 s). The total amount of alcohols decreased after 25 days in DBD-CP-treated samples, more remarkably that of 1-octen-3-ol and benzyl alcohol. Alcohols are known as the secondary products of fatty acid oxidation, especially resulting from catabolism of unsaturated fatty acids. Among alcohols found in DBD-CP treated brown rice, benzyl alcohol, 1-hexanol, and 1-octen-3-ol were heavily present in treated samples compared to the control, which make such alcohols ideal markers of the chemical volatile profile in DBD-CP-treated brown rice. In addition, some alcohols were increased by all studied conditions such as 1-hexanol. In a different study, the researchers investigated alcohol levels in a fresh-cut cantaloupe treated by CP and in control samples; alcohols in the fresh-cut cantaloupe reached the peak value at day 2 and then decreased rapidly during cold storage. However, plasma-treated cantaloupe slices showed an increased trend up to day 6 but decreased afterward, in which treatment significantly inhibited the decrease of total alcohols at 4 and 6 days (Zhou et al., 2022). In a study made by (Abouelenein et al., 2021) investigating the impact of plasma activated water (PAW) on the volatile profile of rocket leaves at different times (2, 5, 10, and 20 min), a significant increase was observed in total relative abundance of alcohols with PAW-2 and PAW-10 samples. The content of hex-3-en-1-ol, which was detected as a major alcohol in Eruca spp. (Bell et al., 2017; Blažević & Mastelić, 2008; Jirovetz et al., 2002), increased after PAW application. Additionally, PAW treatment increased the content of hexan-1-ol. These two compounds are typical green leaf volatiles (GLVs) produced naturally in plants. They are derived from linoleic acid through the lipoxygenase (LOX) enzymatic route (Hu et al., 2018; Tawfik et al., 2017). The pathway produces hexanal and hex-3-enal by oxygenation of linoleic acid through the catalysis of LOX, which, by further reduction of the aldehydes, produces hexan-1-ol and hex-3-en-1-ol. According to Abouelenein et al. (2021) results, an increase in both compounds was observed with all PAW treatments when compared to controls, with a nonsignificant decrease in hex-3-en-1-ol in PAW-5 and -20. These results agreed with the previous study that reported the increase in the contents of hexan-1-ol and hex-3-en-1-ol in camu-camu pulp. The results explained that either the LOX enzyme was activated by plasma application, or the oxidation of linoleic acid was catalyzed by the reactive oxygen species formed during plasma generation (Campelo et al., 2020b). Further, 1-penten-3-ol, which is significantly correlated with sweet attributes in rocket (Bell et al., 2017), was increased in all PAW-treated samples, with a significant increase in PAW-2. Moreover, the significant increase in the content of pentan-1-ol and phenylethyl alcohol in PAW-2 samples was also observed. Octan-1-ol was significantly increased in PAW-20 samples. On the other hand, phenylethyl alcohol was not detected in PAW-5 samples.

3.2 | Aldehydes

There have been many articles investigating the effects of CP on aldehydes in different fruits and vegetables. For example, Ma and Lan (2015) stated that the quality of the fresh tomato fruit was unaffected significantly by plasma disinfection treatment, and the contents of *trans*-2-hexenal, acetal, and n-hexanal in CP-treated samples were significantly higher than those treated by heat processes. Hexanal in neat juice was 1.6 times less than that in CP-treated juice. However, hexanal components totally disappeared after heat treatment (Ma & Lan, 2015). In the study by Liu et al. (2021), levels of hexanal, benzaldehyde, and 1-nonanal were found to be the main VOCs contributing to the characteristic aroma of plasma-treated and nontreated brown rice, which is in agreement with previous findings (Liu et al., 2018). Aldehydes were the second most abundant classes of aroma compounds after alcohols in all samples. Minor differences were found in levels of hexanal and benzaldehyde among DBD-CP-treated and control samples, and such compounds are typically associated with a grassy odor and contribute to the fresh flavor of rice (Zeng et al., 2009). Among aldehydes, an increase in the hexanal content during storage can be considered an indicator of stale rough rice (Bergman et al., 2000). Voltage power contributed more significantly to a higher variation in the hexanal content in brown rice than the duration of DBD-CP treatment. In the present work, levels of hexanal could be significantly controlled in samples treated at 50 KV. However, a lower voltage (40 KV) was shown to yield significant changes in hexanal level in brown rice. Recently the impact of CP treatment in the fresh-cut cantaloupe stored at 4°C for 10 days was studied on 12 aldehydes and showed that hexanal, nonanal, and benzaldehyde are the most abundant aldehydes. Generally, aldehydes showed fluctuating levels during storage; the treatment significantly inhibited total aldehydes reduction at the beginning of storage from days 0 to 6; however it promoted aldehydes degradation afterward (Zhou et al., 2022). Moreover, Abouelenein et al. (2021) observed nonsignificant changes in the total content of aldehydes in PAW-2, -10, and -20 (treatments at different times). However, a significant increase ($p < 0.05$) in the level of total aldehydes was observed only in PAW-5 samples. A significant increase was observed in the content of 2-methyl propanal, 2-methyl butanal, pentanal, hexanal, octanal, 3-furfural, benzaldehyde, and β-cyclocitral. In addition, a nonsignificant increase was revealed for all the other detected aldehydes. The results evidenced that plasma-treated cells in PAW-5 accumulated higher amounts of several aldehydes compared to the controls. Previous studies have also reported an increase in aldehyde content in guava-flavored whey beverages (Silveira et al., 2019) and milk (Korachi et al., 2015) after plasma treatment. This increase in aldehydes could be attributed to the degradation of several unsaturated fatty acids found, for example, in rocket (Bell et al., 2016) by autooxidation and/or the spontaneous decomposition of hydroperoxides. Such degradation could be the result of the damaging effect of reactive species produced by the plasma, which can initiate lipid peroxidation and produce hydroperoxide, and can then be converted to secondary oxidation products such as aldehydes or shorter fatty acyl compounds (Benedetti et al., 1984; Mead, 1976). However, further studies are needed to confirm these assumptions.

3.3 | Terpenes

The influence of low-pressure cold plasma (LPCP) treatments (1, 3, and 5 min) on the EO content mainly terpenes of lemon verbena leaves was investigated by Ebadi et al. (2019). As shown in Table 1, LPCP processed lemon verbena leaves EO induced a reduction in oxygenated sesquiterpenes and an increase in oxygenated monoterpenes and both monoterpene and sesquiterpene hydrocarbons (Ebadi et al., 2019). The highest geranial and neral concentrations were observed in the control samples, and the lowest in the 3-min LPCP treated samples. Limonene, 1,8-cineole, and γ-elemene contents were slight after 3 min of LPCP treatment. However, highest spathulenol and globulol concentrations were observed after 5-min treatment. In addition Campelo et al. (2020a) evaluated the changes made by CP technology on the flavor profile of camu-camu fruit juice rich in terpenoids and sesquiterpenoids. The application of DBD plasma led to the formation of terpenes including the following: α-bulnesene, cadina-1(2),4-diene, selina-3,7(11)-diene, β-pinene, myrcene, γ-terpinene, and α-humulene camu-camu pulp. However, the contents of α-pinene, limonene, terpinolene, and the sesquiterpenes (α-phellandrene, γ-cadinene, α-calacorene, β-caryophyllene, and germacrene (B)) did not show a common trend, and their concentration varied according to the plasma frequency. Nonsignificant change was observed for phellandrene when DBD plasma was applied at 200 Hz. The highest limonene and α-pinene contents were observed at 960 Hz. Terpinolene decreased after DBD application due to its rearrangement to form γ-terpinene, α-phellandrene, and myrcene (Campelo et al., 2020a). Simple rearrangement reactions shifted by DBD application toward the formation of β-pinene from α-pinene, and camphene was reported (Liu et al., 2008; Yang et al., 2011). Figure 2 depicts the reported complex reactions induced by plasma-reactive species such as rearrangements, hydrogenations, and dehydrogenation, which were observed in sesquiterpenes of the camu-camu pulp treated by DBD plasma. DBD plasma at 420 and 700 Hz and above 12,000 Hz induced a reduction in β-caryophyllene concentration and a significant increase in the other dehydrogenated sesquiterpene compounds. However, processing at 200 and 900 Hz induced an inversed effect in which β-caryophyllene concentration was increased with a consequent decrease in the other sesquiterpene compounds (Campelo et al., 2020a). However, camu-camu pulp processing by glow discharge plasma induced the formation and thus increase of α-pinene, limonene, terpinolene, β-caryophyllene, α-fenchol, borneol, 4-terpineol, and α-terpineol concentrations. On the other hand, a reduction in the contents of α-humulene, α-bulnesene, γ-cadinene, cadina-1(2),4- diene, selina-3,7(11)-diene, α-calacorene, germacrene B, β-pinene, myrcene, and α-phellandrene was also observed (Campelo et al., 2020b).

3.4 | Esters

The effects of CP on esters in different fruits and vegetables have been investigated in previous reports. In the camu-camu pulp treated by DBD plasma, ethyl butanoate did not show a common trend, and its concentration depended mainly on the induction frequency of the

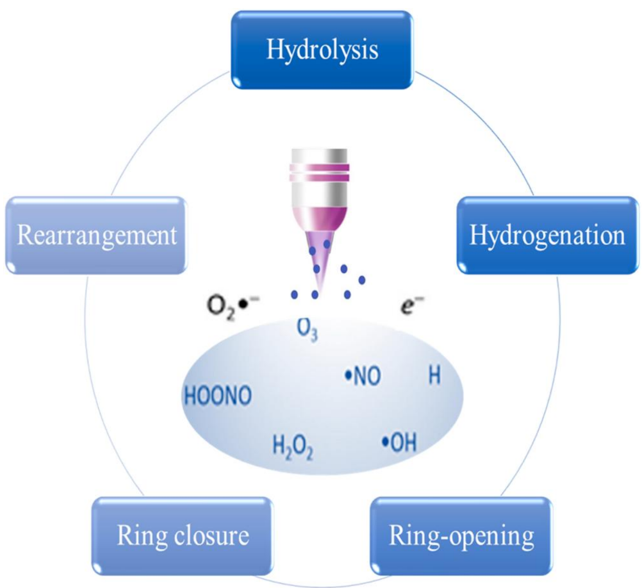

FIGURE 2 Some chemical reactions induced by plasma reactive species on different food volatile components.

plasma (Campelo et al., 2020a). However, in camu-camu pulp treated by glow discharge plasma, an increase in the content of ethyl butanoate was reported (Campelo et al., 2020b). In addition, Ma and Lan (2015) reported the loss of ethyl laurate and octyl formate esters after the CP treatment of tomato juice. Compared with levels of alcohols and aldehydes, the level of esters showed a significant increasing trend in brown rice samples submitted to different DBD-CP treatments, which might be attributed to the presence of peroxide intermediates of oxidation (Liu et al., 2021). Moreover, levels of ketones, phenols, and pyrazines were lower in DBD-CP-treated samples. During the Strecker degradation reaction, amino ketones are generated from amino acids and pyrazines are then produced from the condensation and oxidation of amino ketones (Shi et al., 2018). According to Sacchetti et al. (2016) dissimilar volatile aroma compounds in brown rice could be caused by the concentration of compounds formed as a result of the Maillard and caramelization reactions. With a higher voltage and an extended treatment duration, the etching caused by plasma species on the rice bran layer likely exposed more surface area for reaction (Thirumdas et al., 2016). Total ester contents in control cantaloupe samples reached to the peak at day 2 and then decreased generally over the remaining days up to day 10. However, in CP-treated samples they exhibited a fluctuating level during the storage with maximum value achieved at day 8. Compared with the control, plasma treatment significantly inhibited the reduction of esters during storage (Zhou et al., 2022).

4 | THE EFFECT OF COLD PLASMA ON FLAVOR AND AROMA

4.1 | Flavor

Various chemical reactions that involve a wide range of metabolites, which often lead to the development of volatile aroma compounds, could have happened during food processing. Perception of active volatile compounds formed during chewing is responsible for feeling the flavor by help of taste receptors on the tongue (Shirani et al., 2020). The protection and stability are very crucial for the food industry to produce high-quality food products. Each of the fruit and vegetable juices have their own distinct aromas. The main flavor components, which include esters, alcohols, aldehydes, and acids, also serve as an important evaluation indicator of product quality.

It is challenging to prevent volatile substances from being destroyed during heat processes, which compromises with flavor. CP sterilization offers many benefits over thermal methods. Low processing temperatures, meanwhile, preserved product freshness while preserving the food's nutritional value, color, flavor, and texture. Some of the juices' potential flavor components will be released, and aroma loss is reduced. CP can lower the activity of both polyphenol oxidase (PPO) and peroxidase (POD) in the model food system, according to research on the effects of plasma on enzyme activity. After a treatment period of 180 s, the activity of PPO had decreased by about 90%. After 240 s, POD became more stable and decreased by about 85% (Surowsky et al., 2013). CP treatment had no significant impact on the flavor and aroma of tomato juice, but the change of heat sterilization was significantly higher than control, according to Ma and Lan (2015); also new substances were produced by CP-treated tomato juice, such as 2-hexene aldehyde, and some substances were lost, such as ethyl laurate.

Previous research has shown that flavor fingerprints created by HS-GC-IMS can be used to assess the distinctive aroma of grain products and provide useful information. Liu et al. (2021) reported that flavor fingerprint analysis during storage of brown rice treated with DBD-CP revealed distinct trends from the control. Between treated and control samples, there were differences in the similarity index and signal intensity of characteristic peaks like 3-methyl-1-pentanol, 3-methyl-1-buten-1-ol, 1-hexanol, n-nonanal, and 2-hexanone. In comparison to samples of untreated brown rice, samples treated with a higher voltage (50 kV) and for a longer period showed a lower similarity of flavor fingerprints. Utilizing HS-GC-IMS for untargeted VOC profiling, samples with plasma produced at higher voltages than the control showed 3D signals with lower similarity. PCA plots demonstrate the distinct differences in flavor fingerprints between samples treated with DBD-CP. According to data obtained by HS-GC-IMS, PC1 and PC2 concentrate over 85% of variation among all groups, indicating that untargeted flavor fingerprints contain information that can be used to distinguish between samples of brown rice. Treatment with plasma produced by higher voltage and applied for a longer period reduced the similarity of flavor fingerprints between control and treated brown rice samples. Additionally, Thirumdas et al. (2018) discovered that the voltage and treatment duration had a significant impact on the amount of time that food needed to cook. The accumulation of antioxidants in brown rice as a result of CP treatment can be seen as a stress-generating condition that is beneficial for promoting health (Yodpitak et al., 2019). The findings demonstrated that flavor fingerprints from untargeted metabolomics by HS-GC-IMS can be used to distinguish between variations in brown rice treated with DBD-CP.

Shirani et al. (2020) conducted a multivariate analysis to determine the sensory characteristics of almond slices treated with argon CP. According to the authors, a 10-min CP treatment is preferable from the perspective of the consumer. The flavor of the food may significantly change after being exposed to CP, possibly depending on important food components like fatty acids and proteins. Therefore, it is essential to identify the chemical species in plasma-treated foods that directly affect flavor perception in order to avoid any unfavorable effects of the treatment and provide more accepted food by focusing on the development of favorable flavor characteristics and reducing the incidence of undesirable ones.

4.2 | Aroma

When evaluating the quality of food, a human nose's assessment of sensory qualities is of the greatest importance. Food odors have been shown to have an impact on food portions, food preferences, and even the development of specific food cravings. Odor molecules interact with the olfactory cells in the mucosa and have chemical properties that stimulate chemical senses like aroma and flavor that travel to the olfactory bulb (Buettner & Beauchamp, 2010). The aroma of products that have been treated changes noticeably as a result of CP's interaction with odor molecules (Campelo et al., 2020a). By causing various chemical reactions like molecule rearrangement, hydrolysis, hydrogenation, ring opening, and ring closure, glow discharge plasma significantly affected linoleic acid-derived compounds like terpenes, sesquiterpenes, and green leave volatiles camu-camu pulp. Changes in these volatile compounds are anticipated to have an immediate impact on the aroma profile, especially in the woody, pine, and spicy fragrances. The same team looked into how the flavor and aroma of camu-camu pulp were affected by DBD plasma (Campelo et al., 2020a). It was discovered that under all operating conditions, the pulp was induced to change the aroma profile to some extent. Additionally, as the excitation frequency augmented, the loss of herbal and camphoraceous notes became more significant (Shirani et al., 2020). Plasma-treated almond samples contain C5–C11 aldehydes; the most prevalent by-products of oleic and linoleic acid oxidation. Hexanal, nonanal, and octane can produce an odor that has a negative impact on the quality and aroma of almonds. Storage and oxidation result in an additional increase in these compounds. Chutia et al. (2020) noted a chemical flavor in tender coconut water after plasma treatment and recommended adding 1% orange juice to the mixture to cover it up. Schnabel et al. (2015) discovered comparable outcomes on apple slices that have been treated with plasma. The authors concluded that the observed changes could not be attributed to the plasma therapy. Research on the impact of CP processing on food flavor and odor rely on sensory assessments, which are often performed at a lab scale by untrained panelists. This calls for the commercialization of more sophisticated techniques for sensory evaluation of processed meals to get standardized outcomes. Also, the operating conditions may be properly controlled to influence certain chemical reactions and produce the required aroma alterations.

5 | CONCLUSION

CP is a novel nonthermal technology that has found numerous applications in the food industry recently. It destroys microorganisms, preserves food, and maintains quality without employing chemical antimicrobial agents. On the other side, food processing by CP can be associated with food quality challenges, so research on the applications of this technology and its effects on food quality are increasing. This paper reviews the effect of CP on the volatile profile, flavor and aroma properties of fruits and vegetables. Plasma treatment is associated with the acceleration and increasing of the fat oxidation process in treated food leading to secondary volatile and nonvolatile compound formation such as furans, alcohols, aldehydes, carbonyls, and hydrocarbons. Nevertheless, some volatile compounds could undergo rearrangements and conversions or are even lost through plasma treatment. These changes are in most cases associated with the changes caused by lipid oxidation, Strecker degradation, and Maillard reactions.

In addition, the flavor of the food may significantly change after being exposed to CP, possibly depending on important food components like fatty acids and proteins. Therefore, it is essential to identify the chemical species in plasma-treated foods that directly affect flavor perception in order to avoid any unfavorable effects of the treatment and provide more accepted food by focusing on the development of favorable flavor characteristics and reducing the incidence of undesirable ones. The aroma of products that have been treated changes noticeably as a result of CP's interaction with the odor molecule. By causing various chemical reactions like molecule rearrangement, hydrolysis, hydrogenation, ring opening, and ring closure, plasma significantly affected linoleic acid-derived compounds like terpenes, sesquiterpenes, and green leave volatiles of vegetables and fruits. Changes in these volatile compounds are anticipated to have an immediate impact on the aroma profile, especially in the woody, pine, and spicy fragrances.

Many studies discovered that the voltage, frequency, and treatment duration parameters of CP had a significant impact on flavor and aroma fingerprints. In conclusion, the operating conditions may be properly controlled to avoid any unfavorable effects and provide more accepted food by focusing on the development of favorable flavor and aroma characteristics and reducing the incidence of undesirable ones. Also, more sophisticated techniques for sensory evaluation of processed foods should be developed and commercialized to get standardized outcomes.

AUTHOR CONTRIBUTIONS

Doaa Abouelenein: Writing – review & editing. **Giovanni Caprioli**: Supervision. **Ahmed M. Mustafa**: Writing – review & editing.

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The authors declare no conflicts of interest.

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Research data are not shared.

ETHICS STATEMENT

Not applicable.

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