Received: 6 December 2022 | Revised: 12 July 2023 | Accepted: 3 August 2023

DOI: 10.1111/1541-4337.13231

COMPREHENSIVE REVIEW

Comprehensive REVIEWS in Food Science and Food Safety WILEY

Cold plasma application to fresh green leafy vegetables: Impact on microbiology and product quality

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Funding information
Istanbul Technical University, Grant/Award Number: 43656

Abstract

Fresh green leafy vegetables (FGLVs) are consumed either garden-fresh or by going through very few simple processing steps. For this reason, foodborne diseases that come with the consumption of fresh products in many countries have prioritized the development of new and reliable technologies to reduce food-related epidemics. Cold plasma (CP) is considered one of the sustainable and green processing approaches that inactivate target microorganisms without causing a significant temperature increase during processing. This review presents an overview of recent developments regarding the commercialization potential of CP-treated FGLVs, focusing on specific areas such as microbial inactivation and the influence of CP on product quality. The effect of CP differs according to the power of the plasma, frequency, gas flow rate, application time, ionizing gases composition, the distance between the electrodes and pressure, as well as the characteristics of the product. As well as microbial decontamination, CP offers significant potential for increasing the shelf life of perishable and short-shelf-life products. In addition, organizations actively involved in CP research and development and patent applications (2016–2022) have also been analyzed.

KEYWORDS

cold plasma systems, fresh green leafy vegetables, microbial decontamination, plasma, product quality

1 | INTRODUCTION

The United Nations General Assembly has declared 2021 as the “International Year of Fruits and Vegetables” to draw attention to its importance in human health and nutrition (Food and Agriculture Organization [FAO], 2021). Regular consumption of fresh green leafy vegetables (FGLVs) is reported to reduce the risk of stroke, hypertension, cardiovascular, and other chronic diseases eventually increasing life expectancy and quality (Lee et al., 2022; Uhlig et al., 2022). FGLVs contain high levels of carotenoids, tocopherols, flavonoids, phenolic compounds, vitamins, minerals, and dietary fiber (Bhamdare et al., 2022). Ready-to-eat FGLVs are intended to be used as raw material in diet and therefore go through gentle processes of washing and packaging to get the most out of their nutritional value (Arienzo et al., 2020; Losio et al., 2015; Park et al., 2012). FGLVs have been reported to be contaminated with disease-causing pathogens (*Escherichia coli*, *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, *Shigella* spp., *Yersinia* spp., *Cryptosporidium*, *Cyclospora*) and a wide variety of enteric viruses such as noroviruses and hepatitis A virus from irrigation water, operating environment, and/or handling personnel (Bosch et al., 2018; Callejón et al., 2015; Ferrario et al., 2017). To ensure microbial safety on FGLVs, different methods, such as chlorine, chlorine dioxide, hydrogen peroxide (H_2O_2), ethanol, ozonated and electrolyzed water, peracetic acid as well as organic acids (malic, lactic, citric, tartaric, acetic, propionic, succinic, etc.), radiation, high hydrostatic pressure, continuous electric field, gamma radiation, ultrasound, and ohmic heating and ozone applications are applied or being tested (Chakka et al., 2021; Denoya et al., 2021; Khan etal.,2018 Sagong et al., 2011; Song et al., 2022; Wang et al., 2019; Zhang et al., 2022). Although the common practice for decontamination is chlorine application, studies demonstrate that organic substances in water combine with chlorine, leading to carcinogenic trihalomethane (THM) and other halogenated hydrocarbons (Trevisani et al., 2017). Similarly, the use of ethylene oxide is prohibited in the European Union, as it may cause carcinogenic by-products (Hertwig et al., 2015). For this reason, new and more reliable technologies are needed to reduce foodborne diseases and food-related epidemics that come with the consumption of ready-to-eat fresh products (Kotzekidou, 2016; Becker et al., 2019).

Cold plasma (CP) application is one of the innovative technologies proven to decontaminate the target pathogen with minimal damage to product quality and nutrient content, and without causing a significant temperature rise in food products. This technology has also been applied to many foods, such as meat and dairy products, fresh fruit, and vegetables (Fernandez et al., 2013; Zhang et al., 2013). Unlike traditional applications, CP application has been providing microbial decontamination with the hurdle effect of ultraviolet (UV) radiation, electrons, ions, free radicals, and excited molecules. CP targets the cell membrane of pathogens, and microbial cell death occurs by abrasion, electroporation, oxidation, and DNA modification on the membrane surface (Oh et al., 2017). Compared to other methods used in the surface decontamination of FGLVs, the CP system has a relatively simple and inexpensive design, does not require a long processing time, does not cause toxic residue formation in the product, and requires less water for rinsing after processing (Min et al., 2017).

CP applications have seen significant growth in recent years in the conduct of R&D activities in many sectors of the food industry worldwide. In this study, we have identified more than 60 companies, universities, and research institutes that have filed CP patent applications for microbial destruction, food and agricultural processing, and the production of packaging materials (Table 1). The majority of patent applications made in connection with R&D activities originate in the United States. The total number of patents has increased more than four times between 2016 and 2022. By nationality, US inventors were followed by Korea, the United Kingdom, and the Netherlands. The distribution of patent ownership between academic institutions and the private sector represents a trend toward the private sector. We have also identified 25 companies/institutes producing commercial CP systems for food-related industries through web research (Table 2). The analysis of companies producing CP systems for food-related industries revealed that R&D companies originating in Germany have the leading position, followed by the USA and France, respectively.

The purpose of this review is to evaluate recent developments in microbial decontamination that CP on freshly consumed green vegetables and further analyze potential technological developments and future prospects of the technological application.

2 | CP VARIETIES COMMONLY USED IN FGLVS

2.1 | Definition of plasma

Plasma, a fully or partially ionized quasi-neutral gas, is the fourth state of matter after the solid, liquid, and gas states and makes up more than 99% of the universe. Plasma is a collection of positively and negatively charged particles that are completely electrically neutral and move in random directions (Von Keudell & Schulz-Von Der Gathen, 2017). Plasma consists of many different species, such as positive and negative charged atoms/molecules, photons (UV, visible, infrared, and thermal radiation), free radical atoms/molecules, electrons, reactive oxygen species (ROS), reactive nitrogen species (RNS), neutral gas atoms/molecules in the ground, or higher state of excited species, including metastables and electromagnetic fields (Michelmore et al., 2016). Plasmas in laboratory conditions are generated at low pressure or atmospheric pressure by adding energy to a gas. The energy may come from thermal, chemical, electrical, radiation (lasers, UV photons), beams (electrons), or by injecting electromagnetic waves (Treumann et al., 2008). Laboratory plasmas produced for food applications are typically generated by applying an electrical voltage to gases, such as air, helium, neon, or argon. Atmospheric pressure plasmas produced using only atmospheric air are of very low cost in terms of food applications.

2.2 | Plasma chemistry: CP varieties commonly used in FGLVs

The chemistry that occurs within a plasma is frequently complex and encompasses many elementary reactions.

TABLE 1 Cold plasma patents related to food applications at US patent office.

Innovation (*method, system, apparatuses, devices, product, application, etc.*)	System features	Companies	No. of patents	Patent date
Elimination of microorganisms (*Pathogenic bacteria, virus, molds and yeast*)				
Method and apparatus for cold plasma food contact surface sanitation	Elimination of microbiological pathogen or denaturing a protein in food	Plasmology4, Inc. (Scottsdale, AZ/USA)	1	2016
Method and system for treating packaged products (decontamination of product)	Insignificant increasing the bulk temperature of the product (atmospheric nonequilibrium plasma [ANEP])	Purdue Research Foundation (West Lafayette, IN/USA)	2	2013, 2017
Inactivating pathogenic microorganisms using cold plasma	Adjusting acidity, especially in liquid foods, with high voltage atmospheric cold plasma (HVACP)	Purdue Research Foundation (West Lafayette, IN/USA)	1	2019
Cold plasma sanitation for a dispensing machine	The sanitizing system comprises a processing unit having a discharge cell configured to initiate a cold plasma discharge in an air flow (ozone-containing water)	PepsiCo, Inc. (Purchase, NY/USA)	3	2015, 2018, 2020
Method and apparatus for cold plasma food contact surface sanitation	Elimination of microbiological pathogen or denaturing a protein in food (with DBD electrode device)	Cold Plasma Medical Technologies, Inc. (Scottsdale, AZ/USA)	2	2014, 2016
Cold plasma decontamination device	Ensuring decontamination of large surface areas	Bovie Medical Corporation (Clearwater, FL/USA)	2	2013, 2014
Plasma generation method and apparatus	Bacteria sterilization and deodorization (even in the presence of steam or fine water droplets)	Samsung Electronics Co., Ltd (Suwon-Si, S. Korea)	2	2013, 2014
Synergistic cold sterilizing and preserving method for fresh meat with high-voltage electric field plasma and nano photocatalysis	Packaging material with photocatalytic bacteriostatic function	Nanjing Agricultural University (Nanjing, China) and Wens Foodstuff Group Co., Ltd. (Yunfu, China)	1	2019
Water purifier and water purification system (for the home, irrigation system, and the pharmaceutical industry)	High-voltage plasma unit (DBD)	Plasma Innova S.A. (San Jose, CR/USA)	1	2022
Sterilization of plant material	Method and apparatus for sterilizing plant material	Cold Plasma Group Inc. (Kingston, CA/USA)	1	2022
Methods of disarming viruses using reactive gas	High-voltage atmospheric cold plasma (HVACP), voltage of 20–150 kV	NanoGuard Technologies, LLC (St Louis, MO/USA)	1	2021

(Continues)

TABLE 1 (Continued)

Innovation (*method, system, apparatuses, devices, product, application, etc.*)	**System features**	**Companies**	**No. of patents**	**Patent date**
Sterilization of packaged articles	Cold plasma is produced from air trapped inside the package	Snowball; Malcolm Robert (Essex, UK)	1	2012
"	"	Ozonica Limited (Northamptonshire, UK)	2	2016, 2019
Cold plasma devices for decontamination of foodborne human pathogens	Contains dielectric layer	The Board of Regents for Oklahoma State University (Stillwater, OK/USA)	1	2019
Method and system for enhancing the efficacy using ionized/aerosolized hydrogen peroxide in reducing microbial populations, method of use thereof	Cold plasma–activated ionized hydrogen peroxide (iH_2O_2)	TOMI Environmental Solutions, Inc. (Frederick, MD/USA)	1	2020
Method and device for disinfection of liquid	Energy-efficient disinfection or sterilization of contaminated liquid, such as water contaminated with viruses or microbes includes an asymmetric configuration of a cavitation nozzle made from a dielectric material that enables the formation	Jozef Stefan Institute, National Institute of Biology, and University of Ljubljana (Slovenia)	1	2022
System and method for food sterilization	Utilizing microwave-generated plasma	Samu Technology, LLC (Fremont, CA/USA)	1	2021
In-package plasma surface sterilization system and methods	Dielectric Barrier Discharge (DBD)	Campbell Soup Company (Camden, NJ/USA)	1	2018
Plasma cleaning method	Cleaning and decontamination of instruments	The University Court of the University of Edinburg (Edinburgh, UK)	1	2010
Self-sterilizing device using plasma fields	A method and apparatus for self-sterilizing a surface or other portion of the apparatus and/or sterilizing other objects	University of Florida Research Foundation Inc. (Gainesville, FL, USA)	1	2011
Method and system for reducing pathogens	A method and system are provided whereby pathogens in food are reduced by first sealing food in a package and then applying high hydrostatic pressure to the sealed package	Shutts & Bowen, LLP (Tampa, FL/USA)	1	2010

(Continues)

TABLE 1 (Continued)

Innovation (*method, system, apparatuses, devices, product, application, etc.*)	**System features**	**Companies**	**No. of patents**	**Patent date**
Cold plasma generating apparatus and multi-cold plasma array apparatus comprising the same	Cold plasma apparatus for applications related to sterilization	PSM Inc. (Gyeonggi-do, Korea)	1	2021
Food sanitization	Cold plasma treatment may be used to sanitize the surface of porous foods	Mars, Incorporated (McLean, VA/USA)	1	2017
Sterilization apparatus	In sterilization of container for food, bottle caps, medical devices, foodstuff such as vegetables and meat, and the like	Suntory Holdings Limited (Osaka, Japan) and Plasmatreat GmbH (Steinhagen, DE/Germany)	1	2018
Plasma sterilizer apparatus for pipe	Sterilization	Korea Food Research Institute (Jeollabuk-do N/A, Korea)	1	2020
Atmospheric-pressure plasma decontamination/sterilization chamber	An atmospheric-pressure plasma decontamination/sterilization chamber is described	The Regents of the University of California (Los Alamos, NM/USA)	1	2001
Food processing				
Cooking device	The system is including low-pressure gas chamber, plasma-igniting means, cooking enclosure formed of metal	Wright; Andrew Clive (Sale, UK)	1	2021
Method and apparatus for plasma-assisted laser cooking of food products	A method and apparatus are disclosed for applying laser energy to a food product to affect the cooking thereof	Singh; Inderjit (Singapore)	1	2013
Microwave plasma cooking	Provides cooking very quickly while maintaining flavor, texture, appearance, smell, and taste	Weingarten, Schurgin, Gagnebin & Lebovici LLP (Boston, USA)	1	2009
Cooking apparatus with plasma cleaning	A cooking apparatus includes a case in which a cooking chamber for cooking food is provided, a heating source provided in the case, a fan configured to circulate air in the cooking chamber; and a plasma discharger provided in the case and configured to generate plasma in order to remove residue from a surface of the case	Mckenna Long & Aldridge LLP (Washington, DC/USA)	1	2009
“	“	LG Electronics Inc. (Seoul, Korea)	1	2011

(Continues)

TABLE 1 (Continued)

Innovation (*method, system, apparatuses, devices, product, application, etc.*)	System features	Companies	No. of patents	Patent date
Cook-in package and method of making same	Pure oxygen or a mixture of oxygen and nitrogen containing less than 30% nitrogen	Cryovac, Inc. (Duncan, SC/USA)	1	1999
Surface plasma treatment and coating of food products	The method can include generating an activated gas by introducing a working gas into a plasma chamber and generating nonthermal plasma in the plasma chamber, where the working gas and the nonthermal plasma interact to form an activated gas	Campbell Soup Company (Camden, NJ/USA)	1	2018
Method and apparatus using microwave energy	The process generates energy from organic material utilizing microwaves	Brooks Kushman P.C. (Southfield, MI/USA)	1	2006
Method and apparatus to infuse water with nitrate (NO_3) and nitrite (NO_2) using electrical plasma for use in plant fertilization	Nitrogen-enriched water	Salerno; Mark (Huntington, NY/USA)	1	2018
Food processing equipment with plasma-activated water cleaning	A food processing system that includes at least one food and/or feeds processing device and at least one cleaning device	Gea Food Solutions Bakel B.V. (Bakel, Holland)	1	2021
Method and apparatus for extending the shelf life of ozonated water	The method and apparatus for significantly extending the shelf life of an inert gas-infused fluid	Talamantez; Carla (Bullhead City, AZ), Strnad; John (Woodburn Bay, OR), Thompson; Bruce A. (Granite Bay, CA/USA)	1	2020
Process for the treatment of fruits and vegetables (especially for apples and pears)	The present invention is directed to a process for the treatment of fruits and/or vegetables, and especially for the coating of pomes, such as apples and pears	Hoefnagels; Johannes Adrians Maria (Haaren, Holland)	1	2016
Production of hydrogenated vegetable oil without any trans fatty acids	High-voltage atmospheric cold plasma (HVACP)	Purdue Research Foundation (West Lafayette, IN/USA)	2	2020

(Continues)

TABLE 1 (Continued)

Innovation (*method, system, apparatuses, devices, product, application, etc.*)	System features	Companies	No. of patents	Patent date
Systems and methods for reactive gas–based product treatment	The system includes a high-voltage plasma reactor integrated into the processing vessel Does not harm the quality characteristics of the product Suitable for larger raw food quantities The system obviates the need for packaging of product during pasteurization processing	Clean Crop Technologies, Inc. (Arlington, VA/USA)	2	2021, 2022
Plasma-activated fluid processing system	The invention relates to a plasma-activated fluid processing system	VitalFluid B.V. (Eindhoven, Holland)	1	2022
System and method for preserving stored foods	Such as a potato storage facility a system and method for preserving stored foods	Weiss & Moy PC (Scottsdale, AZ/USA)	1	2002
Nitrite substitute comprising mixture of plasma-treated vegetable and egg white	The method includes mixing the nitrite substitute with raw materials of food to prepare a food emulsion	Seoul National University R&DB Foundation (Gwanak-gu, Seoul/Korea) and The Industry & Academic Cooperation in Chungnam National University (ICA) (Yuseong-gu, Daejeon, Korea)	1	2022
Grilling method for controlling content of polycyclic aromatic hydrocarbons in charcoal-grilled meat	No food additives required Reduces the content of polycyclic aromatic hydrocarbons Increases safety while preserving the flavor of food and saves cost	Nanjing Agricultural University (Nanjing, China) and Wens Foodstuff Group Co., Ltd. (Yunfu, China)	1	2022
Agriculture processing				
Method and apparatuses for cold plasma in agriculture	Generating a plasma discharge in a gas or a liquid environment and applying the gas/liquid to a plant	Plasmology4, Inc. (Scottsdale, AZ/USA)	1	2021
Method for introducing substance into plant cell using plasma	The method makes it possible to easily and highly efficiently introduce the substance into the cell without causing damage regardless of the types of the plant and tissue from which the plant cell is derived	National Agriculture and Food Research Organization, Tokyo Institute of Technology (Tsukuba-shi, Ibaraki, Japan)	1	2019

(Continues)

TABLE 1 (Continued)

Innovation (*method, system, apparatuses, devices, product, application, etc.*)	System features	Companies	No. of patents	Patent date
Methods and apparatuses for treating agricultural matter	Methods and apparatuses to activate, modify, and sanitize	APPLIED QUANTUM ENERGIES, LLC (Naples, FL/USA)	1	2020
Packaging material application				
Barrier film	A barrier film for use in laminated packaging materials for liquid food products	Tetra Laval Holdings & Finance S.A. (Pully, Switzerland)	1	2020
Multilayer metallized film and production method description	To increase the barrier effect of a metalized film intended for use in the packaging, in particular of food products, a particular composition of the plastic layer is suggested, on which the metal layer is deposited by vacuum evaporation	Mcglew & Tuttle, PC (Scarborough, NY/USA)	1	2008
Polymer film capacitor	Production of polymer films with superior thermal and mechanical properties	Yializis, Angel (Tucson, AZ/USA)	1	2001
Process to deposit diamond like carbon as surface of a shaped object (include entire food and drug industries)	Uniform hydrogenated amorphous carbon (also called diamond-like carbon, DLC) films on inner surfaces of plastic bottles is successfully deposited	Council of Scientific and Industrial Research (New Delhi, India)	1	2012
Food container having improved oxygen barrier properties and manufacturing method thereof	Thickness of 5–30 nm	Cj CheilJedang Corporation (Seoul, Korea)	1	2014
High-flux ultrasensitive detection dot array enhancement chip	Food safety (Au nano-material)	Jiangnan University (Wuxi, China)	1	2021
Generation of micro biocide inside a package utilizing a controlled gas composition (Air, O_2, N_2, CO_2, He, Ar)	Atmospheric nonequilibrium plasma (ANEP)	Purdue Research Foundation (West Lafayette, IN/USA)	3	2014, 2015, 2016

TABLE 2 Companies producing cold plasma systems for food-related industries.

Company	Claim	Websites
Acxys, France	Provides surface cleaning and decontamination applications for metals, glass, paper, cardboard, polymers (polypropylene, polycarbonate, polyethylene, PVC, etc.), and composite materials	https://www.acxys.com
ADTEC, United Kingdom	Design applications with cold atmospheric pressure gas plasma products	https://adtecplasma.com
APS, United States	Develop systems for waste-to-energy processes, high-temperature surface modification, air sterilization, and engineering	https://www.advancedplasmasolutions.com
AFS, Germany	Produce systems for treatment and modification of surfaces	https://www.afs.biz
COMET PCT, United States	Produce technologies for coating devices (for encapsulation, heating, welding, medical procedures, food packaging)	https://pct.comet.tech
CPI, France	Makes polymer film (including fluoropolymers) nanocoatings with atmospheric plasma	https://www.cpi-plasma.com
Diener, Germany	Produce plasma systems for surface process steps, such as activation, printing, bonding, or foiling on PP, PE, or recycling materials	https://www.plasma.com
Enercon, United States	Manufactures plasma surface treatment equipment, flame treaters and corona surface treaters that clean, etch, and functionalize surfaces for a variety of ink, printing, coating, laminating, painting, adhesive, and bonding applications for plastics, polymers, films, foils, and metals	https://www.enerconind.com
Europlasma, France	Develop plasma systems to reduce the impact of waste on the environment and recycle energy or turn it into valuable products	https://www.europlasma.com
Henniker Plasma, United Kingdom	Design and manufactures innovative plasma surface treatment systems	https://plasmatreatment.co.uk
MPG, Germany	Produce equipment to automotive, electronics, and medical device industries	https://molecularplasmagroup.com
neoplas GmbH, Germany	Develop decontamination and surface cleaning of plastic devices with narrow cracks, capillaries, and the smallest drill holes can be accessed easily under 40°C	https://www.neoplas.eu/en/industry.html
Nordson, United States	Provides curing equipment for powder coating, liquid spray painting, food and beverage can production, and precision dispensing of ambient temperature adhesives or sealants	https://www.nordson.com
PlasmaLeap, Australia	Developing nonthermal plasma-driven chemical reactors for tertiary water treatment and synthesis of green fuels and chemicals	https://www.plasmaleap.com
Plasmatreat, Germany	Development functional coatings, material combinations, and manufacturing processes	https://www.plasmatreat.com
Plasmawise, France	Treatment, disinfection, and removal of organic pollutants	https://www.plasmawise.com
Primozone, Sweden	High ozone concentration and high ozone capacity/output	https://www.primozone.com
P2i, United Kingdom	Ultrathin liquid protection coatings	https://www.p2i.com

(Continues)

TABLE 2 (Continued)

Company	Claim	Websites
Relyon, Germany	Packaging pre-treatment before bonding plastics such as PP, PE, or recycling materials	https://www.relyon-plasma.com
SOFTAL Corona & Plasma, Germany	Manufacture systems for a plasma-based treatment of paper, plastic, metal, and fabric surfaces	https://www.softal.de
Surfx, United States	Designing Argon plasma systems for surface cleaning	https://www.surfxtechnologies.com
Tantec, Denmark	Manufactures standard and customized plasma and corona systems for the surface treatment and plasma etching of plastics and metals	https://tantec.com
Terraplasma, Germany	Applications in medical technology, manufacturing, hygiene, odor management, surface modification	https://www.terraplasma.com
Thierry, Germany	To change the surface energy of packaging and packaging materials to facilitate and improve the adhesion of adhesives, coatings, and inks	https://www.thierry-corp.com
UNIQAIR, United States	Application to control flue odor emissions	https://www.uniqair.com

The basic types of reactions that occur within the plasma are categorized into homogeneous reactions, such as excitation/de-excitation, ionization, dissociation, attachment, charge exchange, and recombination, and heterogenous reactions, such as etching, adsorption, deposition, recombination, sputtering, and polymerization. Heterogeneous reactions take place between the species of plasma and the surface in contact with the plasma; on the other hand, homogenous reactions occur only between the species of plasma. The heterogeneous reactions are particularly important in the processing of FGLVs, which can result in some new chemical reactions. When the FGLVs are treated by CP, they are exposed simultaneously to charged particles (electrons and ions), UV/visible/infrared/thermal radiation, ROS, such as ozone (O_3), superoxide ($O_2{}^-$), electronically excited oxygen (O_2 ($^1\Delta$)), atomic oxygen (O), hydroxyl radical (OH), and hydrogen peroxide (H_2O_2), RNS, such as atomic nitrogen (N), electronically excited nitrogen (N_2(A)), nitric oxide (NO), dinitrogen tetroxide (N_2O_4), nitrous oxide (N_2O), and nitrogen dioxide (NO_2), and other ground or higher states of excited atomic and molecular species of working gas (Stoffels et al., 2008).

As shown in Figure 1, the production and transport of reactive species are carried out in a series of stages, such as plasma physics, plasma chemistry, solution chemistry, biochemistry, and food chemistry. The species are generated in the plasma initially and then continue to pass through the post-plasma (afterglow), before making contact with FGLVs. The elementary processes involved in the production and transportation of reactive species are significantly different from one stage to another. The primary reactive species generated by plasma are electrons, ions, excited species, and light. However, secondary reactive species may be created as a result of plasma interacting with humid air; these include O, $O_2{}^-$, O_3, OH, NO, and NO_2. When a CP comes into direct contact with the surface of FGLVs, a series of changes occur before the plasma-generated species make contact with the FGLVs. The primary and secondary species begin to interact with the species emerging at the surface of the FGLVs, and they can cause the generation of new species, such as H_2O^+, OH, O, H, NO, O_2, $O_2{}^-$, HNO_3, H_2O_2, HNO_2, O_3, and electrons (Samukawa et al., 2012). In this interaction, a new interface containing different species also be generated on the surface of FGLVs by processes such as sputtering and evaporation. On the other hand, species that are generated from the interface may diffuse into the FGLVs. As a result of different chemical reactions that may occur with this interaction and new species ($O_2{}^-$, NO, NO_2, HNO_3, H_2O_2, HNO_2, ONOOH, $ONOO^-$, O_2NOOH) may also be produced (Lu & Fridman, 2015).

3 | MOST USED CP SYSTEMS FOR FGLVS

CPs can be generated over the wide pressure range from 10^{-4} to 10^5 Pa. In general, systems that produce plasma at pressures less than 100 Pa, achieved using vacuum equipment, can be considered "low-pressure plasma systems," and systems that produce plasma at pressures around 1 atm

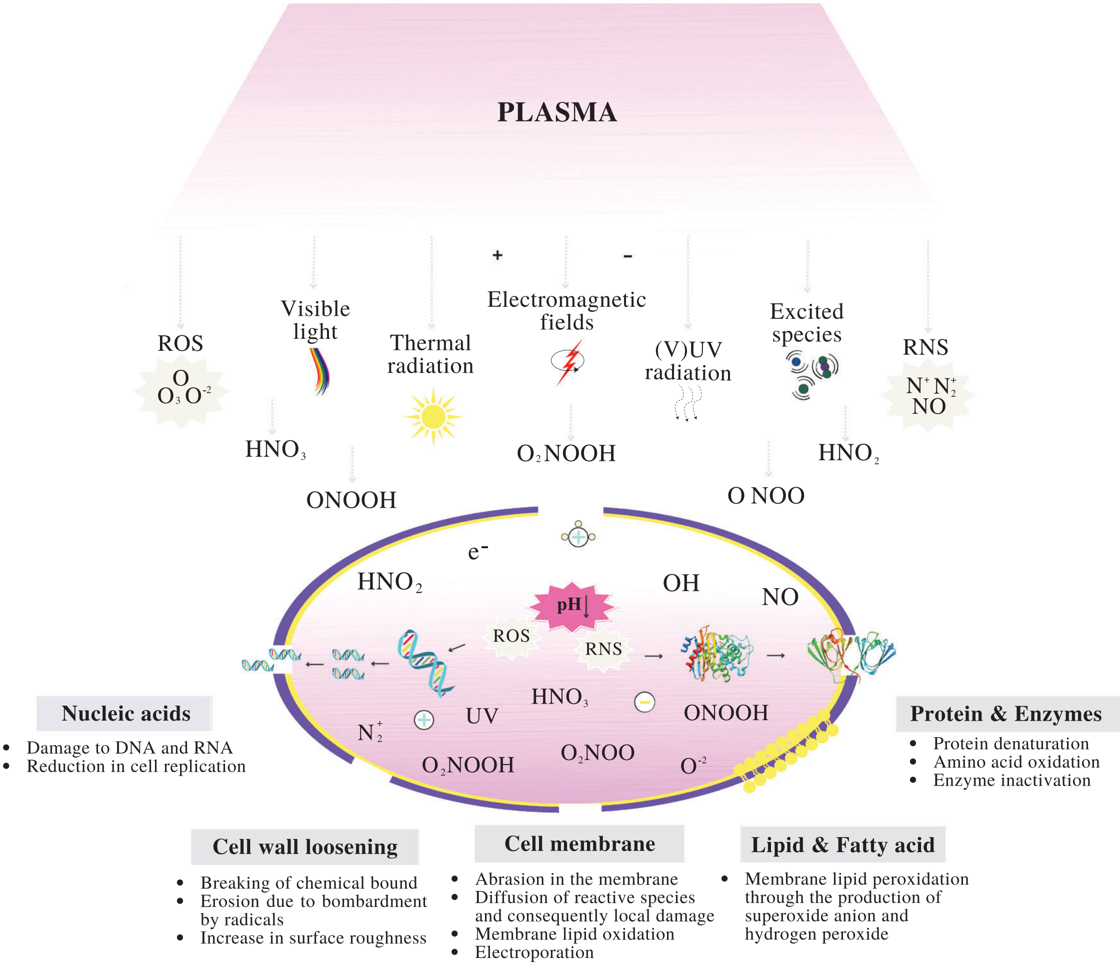

FIGURE 1 Effect of cold plasma technology on microorganism cells.

can be considered "atmospheric pressure plasma systems." The majority of the studies reported on FGLVs up to date used atmospheric pressure plasma systems. This is primarily because CPs generated at low pressures are costly due to the need for vacuum apparatus, whereas atmospheric pressure plasmas using only atmospheric air are low cost and will therefore be most relevant for food processing. The direct or remote application of CPs on FGLVs is also an important factor in the choice of the CP system to be used (Sharma et al., 2018). Direct application is when the FGLVs to be treated are in direct contact with the plasma. All plasma agents (plasma-generated species and electromagnetic fields) come into contact with the FGLV sample. The major identifying property of the direct CP application is that a significant flux of ions and electrons reaches the surface of the FGLVs. The second method is the remote application in which the FGLV sample is placed at a noncontact distance from the plasma. In this application, the ions and electrons do not play a role because they recombine before reaching the FGLVs, and the active species are blown to the treated FGLVs. In the remote application, the active species are delivered to the surface of the FGLVs by a flow of gas through a plasma region. Despite mostly active uncharged species (e.g., O, O_2, OH, NO, and O_3) will be the acting agents, many of the short-lived neutral reactive oxygen or nitrogen species also do not reach the FGLV sample. In direct CP applications using dielectric barrier discharge (DBD), the plasma can choose any part of the FGLV sample as electrodes, causing the localization of the plasma and damage to the FGLVs. Therefore, remote applications in DBD plasmas or CP systems that can make remote applications as a system such as surface DBD (SDBD) and plasma jet are the reasons for preference. Although DBD, SDBD, plasma jet, and corona discharge are atmospheric pressure plasmas generated in atmospheric air, radio frequency (RF), and microwave (MW) discharges can be generated at low pressure to treat the FGLVs (Figure 2). Furthermore, CP processes can be upscaled for continuous production lines by moving or rotating food in sealed containers (or directly) through plasma electrodes on a moving conveyor belt. Compared to plasma jet, corona, and low-pressure discharge treatments, DBD systems have the advantage

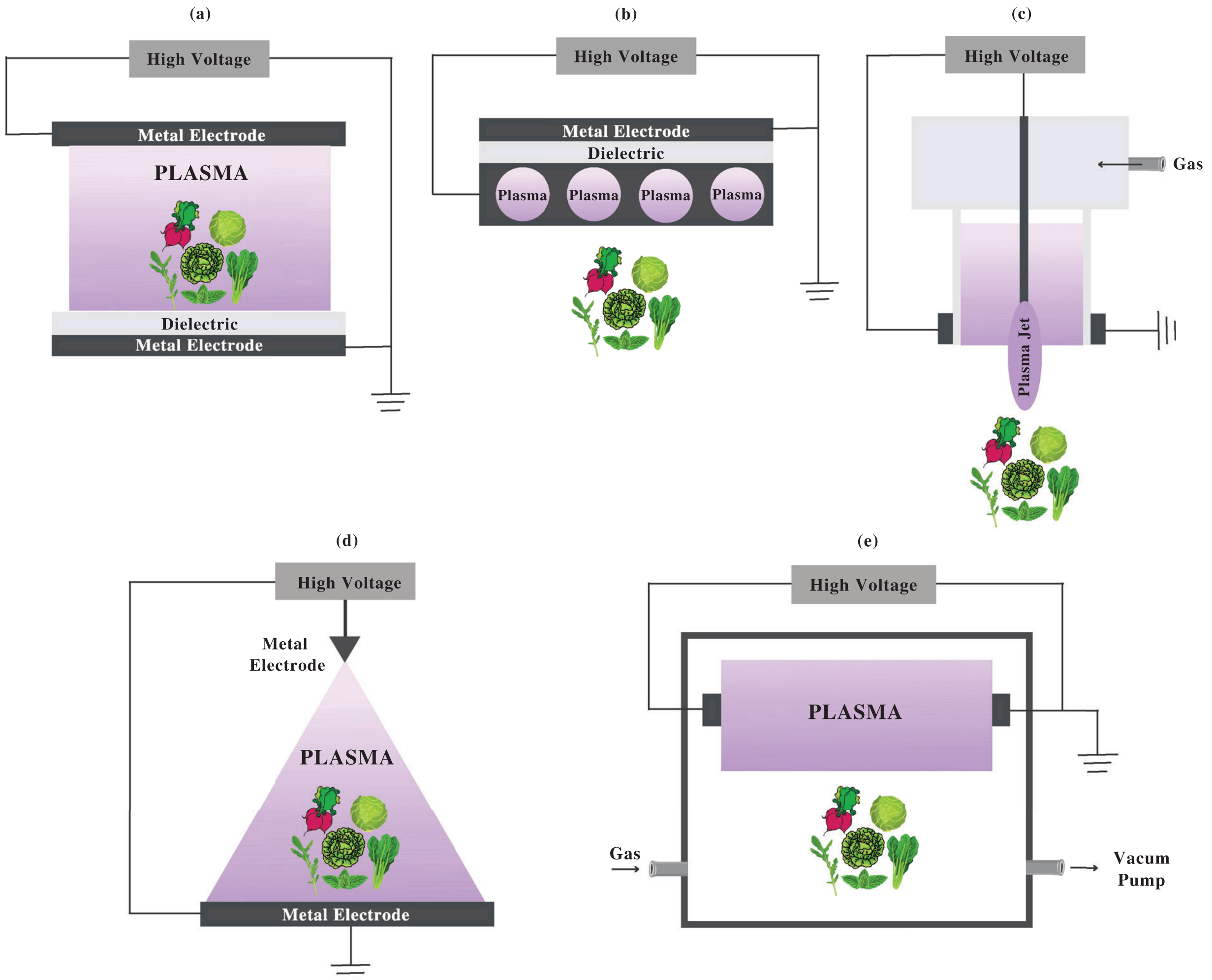

FIGURE 2 Cold plasma systems applied on FGLVs: a) DBD, b) SDBD, c) Plasma Jet, d) Corona discharge, e) Low-pressure.

of much easier upscaling, a simpler power supply unit, and being cost-effective (Bermúdez-Aguirre, 2019; Laroque et al., 2022).

3.1 | Dielectric barrier discharge

A DBD system that typically operates at atmospheric pressure contains electrically insulating dielectric materials (e.g., quartz, glass, ceramics, polytetrafluorethylene—PTFE) that prevent one or two electrodes from directly contacting plasma (Brandenburg, 2017). DBD systems usually contain two parallel plates in planar or cylindrical arrangements (Figure 2a). The dielectric material ensures the prevention of the transition of the discharge to an electrical arc, which could cause the plasma to heat up or damage the FGLVs to be treated. Due to the capacitive structure of the discharge, alternating or pulsed high voltage must be applied between the electrodes. A DBD can be generated by applying a high voltage (10–100 kV) electric alternative current (AC) (or pulsed direct current [DC]) at high frequency (1 kHz to 10 MHz) to a gas inserted at an interelectrode distance (0.1–100 mm).

DBD plasmas can be produced in a volume or on a surface. A volume DBD is generated between two electrodes. At SDBD, the micro discharges are generated on the surface of a dielectric, resulting in a more homogeneous and higher density plasma (Figure 2b) (Bednar et al., 2013). DBDs were applied to FGLVs using different DBD plasma reactors. Table 1 lists some applications of CP produced by different DBD reactors on different FGLVs. CP applications on FGLVs by DBD systems are generally seen to be remote applications. The plasma generated by DBD systems is generally diffuse and covers a relatively large area. Great flexibility is offered by DBD systems regarding their geometrical configuration, operating medium, and parameters. Conditions optimized in laboratory experiments can easily be upscaled to large industrial systems. The use of in-package plasma technology for the DBD treatment of foods is now well established (Ziuzina et al., 2020). It has been designed and fabricated a DBD system well suited to the disinfection of vegetables during sorting on rollers (Toyokawa et al., 2017).

3.2 | Plasma jet

CP jets were applied to FGLVs using different plasma jet reactors. Table 2 lists the application of CP produced by different plasma jet reactors on different FGLVs. The most widely used CP jet system is composed of two electrodes, one of which is connected to high voltage and separated by a glass tube (Figure 2c). The outer electrode has generally a ring shape of metal, and the inner electrode is made from a metallic wire. The discharge ignited between the two electrodes is forced to pass through the glass tube so that the entire gas volume between the electrodes is filled in with plasma drawn from the tube by the gas flow. In the production of plasma jets, gases, such as helium, argon, and their mixtures with air, nitrogen, oxygen, and other gases are commonly used. The dielectric glass prevents streamer-to-spark transitions that could cause the plasma to heat up or damage the FGLVs to be treated. The afterglow (post-plasma) of the electron, neutral, and charged species including photon impinges upon the surface of the FGLVs being processed. When the plasma is generated, it launches a plasma jet that can reach up to 5–10 cm into the ambient air (Lu et al., 2021). The plasma produced by the plasma jet is highly concentrated, has a relatively small diameter, and operates with noble gases, which increases the cost of treatment. If a large area needs to be treated, using a single jet of plasma may not be enough, so multiple jets can be utilized. A large-scale plasma jet system has been developed for the microbial decontamination of particulate foods (Lee et al., 2022).

3.3 | Corona discharge

A corona discharge takes place at or near atmospheric pressure by the application of high voltage (50–100 kV) and produces a luminous glow localized in space around a needle or a thin wire in a highly nonuniform electric field, whereas the grounded electrode may be flat (Figure 2d). The corona discharges can be generated as positive or negative corona considering the polarization of the electrode (Stishkov et al., 2018). Corona discharges were applied to FGLVs using different corona discharge reactors. Table 3 lists the application of CP produced by different corona discharge reactors on different FGLVs. Because corona discharges produce small volumes of plasma such as plasma jets, it is difficult to apply in large areas and there is a high probability of transition to spark or arc plasmas that will damage the applied food. To expand the coverage area of corona plasma for food applications, a multipoint-plate electrode configuration is becoming increasingly popular. This configuration can generate a more energetic and dense plasma compared to DBD, producing a diffuse discharge that covers a much larger surface area of the sample than a pin-tip discharge (Scally et al., 2021). Venkataratnam et al. (2019) investigated the efficacy of corona discharge on major peanut allergens using a large gap multipoint-plate reactor.

3.4 | Low-pressure CP

Table 4 lists the application of CP produced by different low-pressure discharge plasma reactors on different FGLVs. Low-pressure CP systems can be generated as DC, AC, RF, and MW discharges. These systems are vacuumed by a vacuum pump and operated at low pressures <100 Pa (Figure 2e). An electrical voltage (DC, AC, RF, or MW) is applied to two metal electrodes (cathode and anode) inside the vacuum chamber to generate a low-pressure plasma, in a gas at low pressure. To sustain a DC discharge, the electrodes must be conducting. The frequencies generally used for alternating voltages, the discharges that occur in this case are called AC discharges, are in the range of kHz to GHz. Electromagnetic waves drive these plasmas at frequencies of 1–100 kHz for kHz or 13.56 MHz or 27 MHz for RF or 2.45 GHz for MW. RF discharges can be generated when the gas is exposed to an oscillating electromagnetic field using an induction coil surrounding the vacuum chamber (inductive discharge) or by separate electrodes mounted on the external surface of the vacuum chamber (capacitive discharge) (Liu et al., 2022). MW discharges are generated by a magnetron that delivers the MWs to the process vacuum chamber (Lebedev, 2015). In this way, a high rate of free reactive species is revealed (Muhammad et al., 2018). Despite its high price, it is also used in the food industry (Durek et al., 2022; Lee et al., 2015; Oh et al., 2017; Schnabel et al., 2015).

Foods outgas substantially in low-pressure environments and the consequences of complex plasma chemistry resulting from food-derived volatile molecules entering the plasma state and returning some of these molecules to the food as condensate should be considered (Basaran et al., 2008). Low-pressure reactors require additional technical expertise associated with vacuum systems that present additional challenges concerning throughput rates for food processing. In addition, they require costly vacuum systems, and atmospheric pressure plasmas could be preferred as a cost-effective alternative to low-pressure plasmas.

TABLE 3 Microbial decontamination by cold plasma (CP) in fresh green leafy vegetables (FGLVs).

Product	Provided processing conditions	Target microorganism	Log reduction in microbial load	References
Lettuce	Dielectric barrier discharge Gas: atmospheric air Voltage: 80–120 kV at 50 Hz Sample amount: (5 × 5) cm Distance: 10 mm Treatment: direct and indirect Time: 60–120 s	Planktonic cultures and monoculture biofilms: *Escherichia coli* *Salmonella enterica* *Listeria monocytogenes* *Pseudomonas fluorescens* Mixed culture biofilms: *L. monocytogenes* *P. fluorescens*	After >60 s: significantly reduce in mono- and mixed-species biofilms Up to 120 s: 2.2 4.2	Patange, Boehm et al. (2019)
	Dielectric barrier discharge Gas: atmospheric air Voltage: 70 kV Frequency: 50 Hz Sample amount: (5 × 5) cm Sample weight: each of 1.7–2.4 g Distance: 15 cm Time: 30–300 s	*Salmonella typhimurium* *L. monocytogenes* *E. coli*	4.1–5.1 3.8–4.5 3.0–4.0 In 30 s: in bacterial populations 7 After 300 s: in biofilm populations 5	Ziuzina et al. (2015)
	Corona plasma Gas: atmospheric air UV doses: 200–1250 μWs/cm^2 Time: 50 s	*S. typhimurium*, cultivable indigenous microorganisms ([CIM] and their mixtures 7.0–8.0)	1.7, 1.62, and 1.78	Jahid et al. (2015)
	Low-pressure plasma Gas: N_2, $N_2 + O_2$, He Power: 400–900 W Box: a stainless-steel chamber (43 × 37 × 40) cm Time: 10 min	*E. coli* *S. typhimurium*	2.8 2.8	Song et al. (2015)
	Corona plasma Gas: atmospheric air Temperature: <32.5°C UV doses: 1210–1250 μWs/cm^2 Time: 5 min	*Aeromonas hydrophila*	Up to 15 min: 5.0	Jahid et al. (2014)
	Plasma jet (submerged DBD) Gas: air flow Sample amount: (5 × 5) cm Voltage: 20 kV Frequency: 25.8 kHz Power: 7.45 W Magnetic stirrer: 450 rpm Time: 3, 5, 10 min	*P. fluorescens* *Listeria innocua*	After 5 min: from 2.4 to 4.18	Patange, Lu et al. (2019)
	Plasma jet Gas: O_2, N_2, $O_2 + N_2$ (mixing ratio 1:1) Gas flow: 7.5 and 6 + 6 L min^{-1} Voltage: 10 kV Frequency: 18 kHz Power: 30 W RF power Distance: 15 cm Plasma jet located on the inside-top of an aluminum chamber Time: 30 and 60 s	*Bacillus cereus* *E. coli*	Storage at 6 and 25°C: EP: 3.5–1 EP + O_2: 5–3.5 EP + N_2: 4.5–4 EP + O_2 + N_2: 3–1	Ermis et al. (2021)

(Continues)

TABLE 3 (Continued)

Product	Provided processing conditions	Target microorganism	Log reduction in microbial load	References
	Corona plasma Gas: argon Gas flow: 455.33 sccm Voltage: 3.95–12.83 kV Frequency: 60 Hz Time: 30 s up to 10 min	*E. coli* ATCC 11775	1.6	Bermúdez-Aguirre et al. (2013)
	Plasma jet Gas: N_2 Gas flow: 12 L/min Frequency: 1 kHz Power: 1 W Doses: 1200 and 1250 mWs/cm^2 Distance: 9.5 cm Time: 5 min	*S. typhimurium*	2.72	Fernandez et al. (2013)
	Glow discharge Gas: atmospheric air Gas flow: 70–90 ft/min Sample amount: (5 × 5) cm Voltage: 9 kV Frequency: 6 kHz Distance: 1.5 mm Box: a chamber (15.2 × 15.2 × 30.4) cm affixed to the OAUGDP blower unit Time: 1, 3, and 5 min	*E. coli* O157:H7 *Salmonella* spp. *L. monocytogenes*	30 s^{-1} min: >1 and 2 min: >2 1 min: >2 and 3–5 min: >3 1 min: 1 and 3–5 min: >3, >5	Critzer et al. (2007)
	Corona plasma Gas: N_2 Power: 400–600 W Frequency: 40 kHz Time: 2–30 min	*E. coli* O157:H7	500 W, 3 min CNP: 2.0 400 W, 2 min CNP and 5%, 30 min phage: 5.71	Cui et al. (2018)
	Corona plasma and 7.8% aerosolize H_2O_2 Gas flow: 5.0 mL/min Air pressure: 7 psi Distance: 9 mm Voltage: 17 kV Sample amount: 3 cm Box: a treatment chamber (12 × 12 × 24) in. Time: 5, 8,10, 20, 30, and 60 s	*S. typhimurium* *L. innocua*	2.35–5.50 >5.0	Song and Fan (2020)
Lamb's lettuce	Low-pressure plasma Gas: air Gas flow: 16 SLPM Power: 1.1 kW Frequency: 2.45 GHz Time: 7 s	*Pseudomonas marginalis* *Candida albicans* *E. coli* *Pectobacterium carotovorum* *Staphylococcus aureus*	At 5 min: 5.8 :3.9 <10 min: a linear decrease At 15 min: reduction to detection limit	Schnabel et al. (2015)
Romain lettuce	Dielectric barrier discharge Gas: atmospheric air Frequency: 0–2400 Hz Distance: 5 mm Voltage: 0–76 kV (42.6 kV (1.5 A)) Time: 10 min	*E. coli* O157:H7	In 1, 3 and 5 layers: 0.4–0.8 In 7 layers: 1.1	Min et al. (2017)

(Continues)

TABLE 3 (Continued)

Product	Provided processing conditions	Target microorganism	Log reduction in microbial load	References
Romaine lettuce in the package	Dielectric barrier discharge Gas: atmospheric air, O_2–N_2 Sample amount: (4 × 7) cm Sample weight: ~2 g Voltage: 34.8 kV Frequency: 1.1 kHz Distance: 30 mm Time: 5 min	*E. coli* O157:H7 *Salmonella* *L. monocytogenes* Tulane virus	1.1 0.4 1.0 1.3 (over 90%)	Min et al. (2016)
Lettuce, cabbage	Low-pressure plasma Gas: N_2, He + O_2; 667 Pa and 1 L/min flow Power: 400–900 W Dose: 750 mJ/cm^2 Box: stainless-steel chamber (43 × 37 × 40) cm Time: 10 min	*S. typhimurium* *L. monocytogenes*	N_2, 10 min, 900 W for lettuce and cabbage: 1.5 400 W, 10 min for lettuce: 1.8 ± 0.2 He + O_2, 1–10 min, 400–900 W, and 667 Pa for cabbage: 0.3–2.1	Lee et al. (2015)
	Corona plasma and UV-C Gas: O_2 Sample amount: (5 × 3) cm Power: 2.54 mW/cm^2 (COP) Power: 10, 15, 30 W (UV-C) (180–270 nm, 1.3 mW/cm^2) Time: 5 min	*L. monocytogenes*	3.85 4.06	Srey et al. (2014)
Lettuce and clove oil	Corona plasma Gas: N_2 Power: 400–600 W Frequency: 40 kHz Clove oil amount: (1, 2, and 4 mg/mL) Time: 3 min	*E. coli* O157:H7	2.23	Cui et al. (2016)
Tomato–lettuce mixed salad	Corona plasma Gas: atmospheric air Sample amount: (1 × 1) cm Voltage: 35 kV Frequency: 1.1 kHz Time: 3 min	*Salmonella*	For lettuce: 0.34	Hertrich et al. (2017)
Spinach, lettuce	Low-pressure plasma and 3% H_2O_2 Gas: O_2 Sample amount: (1 × 1) cm Power: 600 W (0.34 W/cm^3) Frequency: 13.56 MHz Interior diameter: 15 cm Distance: 2.5 cm Time: up to 800 s	*S. typhimurium* (LT2)	After 600 s: 3.0 ± 0.9 2.7 ± 1.0	Zhang et al. (2013)
Fresh-cut purple lettuce, kale, and baby spinach	Dielectric barrier discharge Gas: plasma-activated with mist Voltage: 20 kV Power: 30 W Flow: 8 cfm Box: a polypropylene chamber (35 × 35 × 35) cm Time: 5–20 min	*Enterobacter aerogenes*	Respectively for 5 min: 0.4 ± 0.2 0.8 ± 0.1 0.9 ± 0.1 Respectively for 20 min: 0.9 ± 0.1 1.3 ± 0.1 2.0 ± 0.2	Tan and Karve (2021)

(Continues)

TABLE 3 (Continued)

Product	Provided processing conditions	Target microorganism	Log reduction in microbial load	References
Fresh spinach	Dielectric barrier discharge Gas: atmospheric air Sample amount: 20–40 and 0.5–1.5 gVoltage: 0–100 kV Power: 900 W Distance: up to 4.5 cm Electrodes: 1 m long Treatment: static (batch) or continuous mode Time: 2.5 min	*E. coli* NCTC 12900 *L. innocua* NCTC 11299	After static mode: 2.2 After static and continuous mode: 1.7–3.8	Ziuzina et al. (2020)
	Corona plasma Gas: H_2O_2 (7.8%) Gas flow: 9.7 mL/min Sample amount: 5 (∼3 cm thickness (2 × 3 cm)) Voltage: 17 kV Distance: 9 mm Time: 45 s treated and 30 min dwell time	*E. coli* O157:H7 *S. typhimurium* *L. innocua*	1.3 4.2 1.3	Jiang et al. (2017)
	Surface dielectric barrier discharge Gas: atmospheric air Voltage: 2.1 kV Power: circular CPPE ∼6.5 W : two-cone CPPE ∼10 W Frequency: 100 Hz to 2 kHz Electrodes: metallized papers electrodes Time: 2, 5, and 10 min	*E. coli* *L. innocua*	4.6 ± 0.6 4.8 ± 1.7	Wang et al. (2022)
Packaged spinach	Dielectric barrier discharge Gas: air/O_2 Storage conditions: 2–24 h at 5°C Time: 5 min	*E. coli* O157:H7	Significant reduction (N.A.)	Klockow and Keener (2008)
Baby spinach leaves	Dielectric barrier discharge Gas: 100% N gas at high humidity Voltage: 80 kV Frequency: 60 Hz Distance: 5 cm Box: polypropylene container (37.5 × 35.5 × 5.0 cm) Time: 5 min in the indirect exposure	*E. coli* O157:H7 *S. enterica* serovars (*Enteritidis, Typhimurium, Montevideo, Newport*) *Enterococcus faecium*	3.77 3.18	Sudarsan and Keener (2022)
Fresh-cut arugula leaves	Dielectric barrier discharge Gas: atmospheric air Voltage: 6 kV Frequency: 45 kHz Sample amount: 10 g Box: a container (1-L volume) with a lid Storage temperature: 2–6°C Time: 10 min	Total microflora	1.02	Dimitrakellis et al. (2021)

(Continues)

TABLE 3 (Continued)

Product	Provided processing conditions	Target microorganism	Log reduction in microbial load	References
Fresh-cut leafy rocket salad	Surface dielectric barrier discharge Gas: atmospheric air Sample amount: 15 g Voltage: 6 kV Frequency: 45 kHz Storage period: 2, 5, and 9°C Time: 5, 10, 15, and 20 min	Total viable count (TVC) *Pseudomonas* spp. Lactic acid bacteria (LAB) Yeasts and molds	In the tenth minute: 1.020 0.298 0.996 0.493	Giannoglou et al. (2020)
Fresh-cut radish sprouts	Low-pressure plasma Gas: N_2; 667 Pa Gas flow: 1 L/min Power: 900 W Frequency: 2.45 GHz Time: 0, 2, 5, 10, and 20 min	*S. typhimurium*	After 20 min: 2.6 ± 0.4	Oh et al. (2017)
Baby kale (*Brassica oleracea*) leaves	Plasma jet Gas: atmospheric air Gas flow: mist flow rate of four SLPMs Voltage: 26 kV Frequency: 2500 Hz Distance: 1.5 mm Thick: copper inner electrode covered with quartz (1 mm), and an outer stainless-steel electrode pipe (3 mm) Time: 60, 120, 180, 240, 300 s	*E. coli* O157:H7 ATCC 700728	After 300 s: 5.5×10^3	Shah et al. (2019)

Abbreviation: N.A. Not available; UV, ultraviolet.

4 | THE EFFECT OF CP APPLICATION ON MICROBIAL SAFETY AND QUALITY IN FGLVS

4.1 | Effect of CP on microbial decontamination

In the last decade, many studies have been published showing the effectiveness of CP technology for the inactivation of spoilage and pathogenic microorganisms, which are major health risk factors, especially in raw consumed foods (Mao et al., 2021). It is seen that the studies are mostly done on the whole leaves, and the leaves with large surface areas are cut after microbial inoculation. Bacteria cannot enter plant tissue unless there is a natural opening on the plant surface, such as wounds, scratches, or stomata. Therefore, they thrive on the plant surface. Although CP has proven its effectiveness over conventional sterilization methods in terms of surface disinfection in FGLVs, more studies are needed. There are not enough studies in the literature examining the effect of CP application on the microbial decontamination of FGLVs. In this section, the efficiency of CP on the decontamination of natural microflora and pathogen microorganisms on FGLVs is discussed. Table 3 focuses on studies addressing the effectiveness of CP varieties and processing parameters in the microbial decontamination of FGLVs.

4.1.1 | Lettuce

Studies examining the effectiveness of CP on FGLVs have mostly focused on lettuce, spinach, and arugula. Considering the lettuce sample, it has been reported that various plasma forms have been applied, and the disinfection of the lettuce was difficult due to the surface topography in general. Min et al. (2017) investigated the effectiveness of DBD plasma by creating a food environment with 1, 3, 5, and 7 layers in Romaine lettuce. According to the results obtained, researchers have been founded that 0.4–0.8 log CFU/g reduction occurred in lettuce leave samples consisting of 1, 3, and 5 layers, and 1.1 log CFU/g reduction in seven layers in *E. coli* O157:H7. Researchers report that the increase in inhibition efficiency may have been due to the shaking of the container during the procedure. In a study examining the inactivation efficiency of in-pack DBD plasma, a 7 log CFU/mL decrease has been reported in the bacterial populations in lettuce juice in 30 s. On the other hand, a decrease of 5 log CFU/mL over 300 s has been reported in biofilms in lettuce stored in a

TABLE 4 Effect of cold plasma (CP) on the quality parameters of fresh green leafy vegetables (FGLVs).

Product	Quality assays	Reported processing conditions	Results	References
Lettuce	Color, texture, sensory evaluation	Corona plasma Gas: atmospheric air UV doses: 200–1250 μWs/cm^2 Time: 50 s	Insignificant change in parameters	Jahid et al. (2015)
	Shelf life, ascorbic acid concentration, antioxidant activity (ABTS, DPPH), sensory test	Low-pressure plasma Gas: N_2, $N_2 + O_2$, He Power: 400–900 W Box: a stainless-steel chamber (43 × 37 × 40) cm Time: 10 min	– Significant increase in weight loss during storage (10°C) after treatment with N_2-CP – Insignificant change in aw (between 0.96 and 1.0) during storage for 12 days at 4 and 10°C – Lightness because of enzymatic browning and phenolic compound oxidation – Insignificant change in color, ascorbic acid, antioxidant activities, physicochemical properties	Song et al. (2015)
	Color, sensory evaluation	Corona plasma Gas: atmospheric air UV doses: 1210–1250 μWs/cm^2 Time: 5 min	– Insignificant change in sensory evaluation – Insignificant change in color below 15°C	Jahid et al. (2014)
	Color, electron microscopy	Corona plasma Gas: argon Gas flow: 455.33 sccm Sample amount: (5 × 5) cm Sample weight: 1 g Voltage: 3.95–12.83 kV Frequency: 60 Hz Time: from 30 s to 10 min	– After 7 min: significant differences in the color tone of the lettuce – Loss of cell membrane, multiple perforations, fusion between cells, and electroporation	Bermúdez-Aguirre et al. (2013)
	Color, texture, and sensory properties	Plasma jet Gas: N_2 Gas flow: 12 L/min Frequency: 1 kHz Power 1 W Doses: 1200 and 1250 mWs/cm^2 Distance: 9.5 cm Time: 5 min	Insignificant change in parameters	Fernandez et al. (2013)
	Surface-color, texture, sensory evaluation	Corona plasma Gas: N_2 Power: 400–600 W Frequency: 40 kHz Storage condition: 7 days at 22°C Time: 2–30 min	– Positive increase in sensory evaluation – Insignificant change in other parameters	Cui et al. (2018)
Lamb's lettuce	Texture, appearance, odor	Low-pressure plasma Gas: air Gas flow: 16 SLPM Power: 1.1 kW Frequency: 2.45 GHz Storage time: 5, 10, and 15 min in a closed bottle Time: 7 s	Insignificant change in parameters	Schnabel et al. (2015)

(Continues)

TABLE 4 (Continued)

Product	Quality assays	Reported processing conditions	Results	References
Lamb's lettuce (*Valerianella locusta*)	Phenolic profile, surface morphology	Low-pressure plasma Gas: argon Gas flow: 20,000 sccm Frequency: 27.12 MHz Power: 35 W Distance: 8.5 mm Time: 40 s	– Significantly increase on the diosmetin content – Insignificant decrease in polyphenolic or phenolic content at <60 s – Faster degradation of flavonoids than phenolic acids as a result of the combined interaction of various reactive plasma species	Grzegorzewski et al. (2010)
Romaine lettuce	Surface morphology, color, carbon dioxide generation, weight loss	Dielectric barrier discharge Gas: atmospheric air Frequency: 0–2400 Hz Distance: 5 mm Voltage: 0–76 kV (42.6 kV (1.5 A)) Time: 10 min	Insignificant change in parameters	Min et al. (2017)
Romaine lettuce in the package	Color, weight loss, temperature change	Dielectric barrier discharge Gas: atmospheric air, O_2–N_2 Sample amount: ∼4 × 7 cm, weight 2.0 g Voltage: 34.8 kV Frequency: 1.1 kHz Distance: 30 mm Time: 5 min	– Insignificant effect on color – No weight loss – Insignificant temperature change	Min et al. (2016)
Lettuce and cabbage	Color, texture evaluation	Corona plasma Gas: O_2 Sample amount: (5 × 3) cm Power: 2.54 mW/cm^2 (COP) Power: 10, 15, 30 W (UV-C) (180–270 nm, 1.3 mW/cm^2) Time: 5 min	Insignificant change in parameters	Srey et al. (2014)
Lettuce and clove oil	Color, texture, sensory evaluation	Corona plasma Gas: N_2 Power: 400–600 W Clove oil amount: (1, 2, and 4 mg/mL) Time: 3 min	– Increase in *a** value – Insignificant change in other parameters	Cui et al. (2016)
Fresh-cut purple lettuce, kale, and baby spinach	Nitrites, nitrates, pH, H_2O_2	Dielectric barrier discharge Gas: Plasma activated with mist (PAM) Voltage: 20 kV Power: 30 W Water flow rate: 0.98 g/min Flow: 8 cfm Box: polypropylene (35 × 35 × 35) cm Time: 5–20 min	– PAM more effective on flat and smooth surface – More effective at spot-inoculated – Insignificant change in other parameters	Tan and Karve (2021)
Fresh spinach	Color, pH, shelf life, firmness, Brix, FTIR	Dielectric barrier discharge Gas: atmospheric air Sample amount: 20 g Voltage: 0–100 kV Power: 900 W Distance: up to 4.5 cm Electrodes: 1 m long Treatment: static (batch) or continuous mode Time: 2.5 min	Insignificant change in parameters	Ziuzina et al. (2020)

(Continues)

TABLE 4 (Continued)

Product	Quality assays	Reported processing conditions	Results	References
	Color, texture, firmness, appearance, and off-odor	Corona plasma Gas: H_2O_2 (7.8%) Gas flow: 9.7 mL/min Sample amount: 5 g (∼3 cm thickness (2 × 3 cm)) Voltage: 17 kV Distance: 9 mm Time: 45 s treated and 30 min dwell time	– Insignificant effect on color and texture – Insignificant change appearance or smell	Jiang et al. (2017)
Baby spinach leaves	Firmness, color, and visual appearance, weight loss, pH value, texture	Surface dielectric barrier discharge Gas: atmospheric air Voltage: 2.1 kV Power: circular CPPE ∼6.5 W two-cone CPPE ∼10 W Frequency: 100 Hz to 2 kHz Electrodes: metallized paper electrodes Time: 2, 5, and 10 min	– An important change in weight and pH – No change on tissue softening – Surface browning on spinach leaves	Wang et al. (2022)
Packaged spinach	Color	Dielectric barrier discharge Gas: air/O_2 Storage conditions: 2–24 h at 5°C Time: 5 min	– *Air-ANEP*: after 24 h storage in refrigerating yellowish in light areas and brownish–green in dark areas – *O_2-ANEP*: after 24 h storage in refrigeration more than 18 h in light areas, and darker green in dark areas	Klockow and Keener (2008)
Baby spinach leaves	Nitrites, nitrates, pH, and peroxides on leave surfaces	Dielectric barrier discharge Gas: 100% N gas at high humidity Voltage: 80 kV Frequency: 60 Hz Distance: 5 cm Box: polypropylene container (37.5 × 35.5 × 5.0) cm Storage conditions: 14 days storage at 4°C Time: 5 min in the indirect exposure	*Respectively after 2 and 5 min*: 0.25, 500, and 100 ppm and 5, 750, and 350 ppm decrease in nitrites, nitrates, and peroxide concentration *After 2 and 5 min of treatment within 14 days*: 380 and 525 ppm decrease in nitrate concentration, 20 and 22.5 ppm decrease in peroxide concentration and no detected nitrites *After 2 and 5 min treatment*: decrease in pH from 5.90 to 4.37 and from 4.37 to 2.5 due to the formation of nitric acid (HNO_3) and nitrous acid (HNO_2)	Sudarsan and Keener (2022)
Fresh-cut rocket leaves	Shelf life, color, pH, firmness, Total soluble solids (TSS), FTIR	Dielectric barrier discharge Gas: atmospheric air Sample: inside a food container Voltage: 6 kV Frequency: 45 kHz Sample amount: 10 g Box: a container (1-L volume) with a lid Time: 10 min	– Estimated shelf life (h) increase of the rocket: 84% – Insignificant change in other quality parameters	Dimitrakellis et al. (2021)

(Continues)

TABLE 4 (Continued)

Product	Quality assays	Reported processing conditions	Results	References
Fresh-cut leave rocket salad	pH, texture (hardness), color, shelf life	Surface dielectric barrier discharge Gas: atmospheric air Sample amount: 15 g Voltage: 6 kV Frequency: 45 kHz Treatment: a chamber with a SDBD Storage period: 2, 5, and 9°C Time: 5, 10, 15, and 20 min	– Insignificant change in pH and color on product during the whole storage period – The more storage time and temperature the more decline hardness in product – Increase in the shelf life of CAP-treated product by 53, 27, and 18 h, respectively, at 2, 5, and 9°C storage conditions	Giannoglou et al. (2020)
Fresh-cut radish sprouts	Weight loss, aw, color, ascorbic acid concentration, antioxidant activity, shelf life	Low-pressure plasma Gas: N_2; 667 Pa Gas flow: 1 L/min Power: 900 W Frequency: 2.45 GHz Storage conditions: 12 days storage at 4 and 10°C Time: 0, 2, 5, 10, and 20 min	– Significantly lower moisture content – Insignificant change in other parameters	Oh et al. (2017)
Baby kale (*B. oleracea)* leaves	Color, appearance, shelf life, cuticle	Plasma jet Gas flow: mist flow rate of four SLPM Voltage: 26 kV Frequency: 2500 Hz Distance: 1.5 mm Thick: copper inner electrode covered with quartz (1 mm), and an outer stainless-steel electrode pipe (3 mm) Time: 60, 120, 180, 240, 300 s	– Insignificant change in color – Browning of cut leaves by the action of polyphenol oxidase and peroxidase enzymes – Increase in shelf Life (insignificant change in color and appearance for 12 days)	Shah et al. (2019)

polypropylene container at 4 or ~22°C for 0, 24, and 48 h in light/dark ambient conditions. Researchers have reported that the biofilms in lettuce samples kept at 4°C for 48 h were more resistant to CP application, and the inactivation activity might have depended on the storage conditions, the type of bacteria, and the age of the biofilm (Ziuzina et al., 2015). Different research results have reported that changes in light, humidity, and temperature may affect the location of bacteria on the plant surface, biofilm formation, and adhesion to the surface (Golberg et al., 2011; Kroupitski et al., 2009). In addition, it is also known that light stimulates the opening of plant stomata (Martinez-Sanchez et al., 2011). Smet et al. (2019) mentioned the synergistic effect of temperature and CP on microorganisms. The researchers stated that cell recovery became more difficult due to keeping the storage temperature low after CP application. In addition, researchers stated that the combined use of He and O_2 gases significantly increased the shelf life. The gases used in plasma production play an important role in determining the specificity of the reactive species and the type of reaction. Identification of reactive species provides the identification of the reaction occurring in FGLVs and the modifications that occur in biomolecules (Dharini et al., 2022). Another research has reported that the chemical resistance of *Listeria* biofilms increased due to the increase in incubation time in products stored at low temperatures (4°C) (Belessi et al., 2011). Moreover, Gu et al. (2013) has reported that a colony-forming bacterium could use the water pores to enter tomato leaves and cause translocation. Tan and Karve (2021) reported that the inhibition efficiency of the fog-activated DBD plasma increased over time (0.4 ± 0.2 and 0.9 ± 0.1 log CFU/g at the 5th and 20th minute in lettuce leaves), whereas the CP activity has been decreased in the curled, folded, or cracked leaves surfaces. It has been demonstrated in previous studies by different researchers that surface properties, such as roughness, surface deformation, and hydrophobicity, affect inoculation and can affect the adhesion of microorganisms to the surface (Wang et al., 2019). On the other hand, Zhang et al. (2013) compared 3% H_2O_2 and low-pressure plasma and stated that the sanitation efficiency depends on the application time and plasma power density, not the surface structure and hydrophobicity of the products. It has been reported that low-pressure plasma has been more successful in inhibiting *Salmonella typhimurium* LT2 and the decrease in *S. typhimurium* LT2 after 600 s has 2.7 ± 1.0 log CFU for lettuce. In another study using corona discharge to inactivate *Salmonella* in ready-to-eat packaged products, it is reported that the effectiveness of CP depends on the nature of the contamination, the direction of transfer, and the surface structure of the contaminated product (Hertrich et al., 2017). Different research as a result of the use of H_2O_2 (aerosolize %7.8) with corona plasma, in *Salmonella* and *Listeria innocua*, inoculated into Romaine lettuce, have decreased by more than 2.35–5.50 log CFU/piece and more than 5 log CFU/piece, respectively (Song & Fan, 2020). Previous studies have proven that CP leads to the degradation of H_2O_2 by initiating a forward oxidation process and accelerating the production of hydroxyl radicals (Nam et al., 2013). Investigating the effectiveness of sterilization by applying a plasma jet to the lettuce wash water, researchers have reported that the inhibition efficiency in *L. innocua* increased from 2.4 to 4.18 log CFU/g, whereas *Pseudomonas fluorescens* fell below the detection limit within 3 min. Researchers have reported that the different degrees of inhibition in the samples inoculated with the same inoculation technique may be due to the thickness of the peptidoglycan layer (Patange, Lu, et al., 2019). The thinner peptidoglycan layer in the cell wall of gram-negative bacteria can facilitate the passage of reactive species released as a result of plasma application through the cell wall and affect the degree of inhibition (Mai-Prochnow et al., 2016). In another research investigating the effectiveness of corona plasma, it has been reported that the inhibition efficiency of corona plasma is more effective in mixed microbial cultures (Jahid et al., 2015). Investigating the effect of in-pack DBD application at high voltage (80 kV) and different application times (from 60 to 120 s), Patange, Boehm, et al. (2019) reported that mono- and mixed-species biofilms grown at lower temperatures (4°C) increased inhibition due to high voltage and reached the undetectable limit due to increased application time. In addition, researchers have reported that mixed cultures were more affected by DBD plasma. In a different study, Han et al. (2016) have been reported that high voltage and increased ROS increase the inhibition level. Niquet et al. (2018) reported that ROS and RNS released with DBD plasma applied in the package could be preserved for a longer time and the H_2O_2 level increased in 24 h storage. In this way, reactive species increase the inactivation rate by increasing the deformation of the macromolecules of the microorganism (Bourke et al., 2017). However, the mass transfer that may occur as a result of processing packaged food with CP is very important. The interaction of food packaging materials with low molecular weight substances (monomers, plasticizers, and solvents) with food as a result of CP application and their transition to food is a matter of debate and there are not enough studies (Pankaj et al., 2014). In another study, it has been stated that pathogen microorganism inhibition increased depending on the increase in the processing time of DBD on lettuce (Critzer et al., 2007). It has been reported that *E. coli* is less sensitive than *Bacillus cereus* to plasma jet application in combination with ethyl pyruvate (EP), and inhibition increases by 2.5 and 1.5 log CFU/cm^2 respectively, at 25°C compared to 6°C. Additionally, it has been reported that the evaporation rate of EP increases with the increase in temperature, and accordingly, the inactivation efficiency increases (Ermiş et al., 2021). It has been reported that corona plasma causes deformation and high electroporation in the cell membrane with its antimicrobial effect, increased voltage, and application time, and disinfection is easier due to the smooth surface structure of the lettuce leaf (Bermúdez-Aguirre et al., 2013). The cell wall is thinner in gram-negative bacteria and the deformation of the cell surface may be greater against plasma application (Otto et al., 2011). Low-pressure plasma was applied using N_2, N_2–O_2 mixture and provided a 2.8 log CFU/g reduction in *E. coli* and *S. typhimurium* pathogens (Song et al., 2015). Lee et al. (2015) later stated that microbial inactivation with low-pressure plasma varies depending on the gas used and the application conditions. Ambient conditions with low pH can cause stress in cells while reducing the resistance of cells to CP application. Therefore, cells can develop resistance to acidic environmental conditions (Evrendilek & Zhang, 2003). Some studies also have investigated how CP effectiveness changes when barrier methods are applied. For example, when UV-C and corona plasma has been combined, 3.85 log CFU/cm^2 inhibition was obtained with only corona plasma application in *L. monocytogenes*, whereas this value increased to 4.06 log CFU/cm^2 as a result of combined UV-C application (Srey et al., 2014). Apart from these, the natural structure of the vegetable should be considered, as well as the chemical processes applied to destroy biofilms and affect the stroma (Hillegas & Demirci, 2003). A study aimed at removing surface biofilm reported a 5.71 log CFU/cm^2 reduction in *E. coli* O157:H7 biofilms with a sequential application of corona plasma (400 W, 2 min) and bacteriophages (5%, 30 min) (Cui et al., 2018). In a study investigating the synergistic effect of clove oil and corona plasma against *E. coli* O157:H7 biofilms in lettuce, it has been determined that corona plasma increased the antibiofilm activity of clove oil, and the quality of lettuce was slightly adversely affected by the use of corona plasma together with clove oil (Cui et al., 2016). Researchers have reported that clove oil is more effective on biofilms, unlike plasma (Cui et al., 2016). In different studies, it has been reported that the entry of microorganisms into the stoma and the roughness of the lettuce surface reduce the effectiveness of plasma (Fernandez et al., 2013; Srey et al., 2014). Moreover, a different study reported increased the resistance of biofilm populations to corona plasma treatment for greater than 15 min (Jahid et al., 2014). In another study investigating the effectiveness of microbial decontamination in lettuce treated with DBD, it has been also reported that the lettuce has been not affected by the gas in the package or environmental conditions such as humidity. In addition, a reduction of 1.1 ± 0.4, 0.4 ± 0.3, 1.0 ± 0.5, and 1.3 ± 0.1 log PFU/g has been reported in *E. coli* O157:H7, *Salmonella*, *L. monocytogenes*, and Tulane virus, respectively (Min et al., 2016). Unlike corona plasma, DBD plasma has a more intense plasma production capacity and offers convenient use in foods with a larger surface area (Hertrich et al., 2017; Puligundla et al., 2020; Song et al., 2022). In DBD plasma production, Ar, He, or other noble gases can be used as well as an atmospheric gas. Due to their low ionization potential, they enable the production of CP in larger volumes (Ansari et al., 2022). With this aspect, it has come to the fore in recent years as a more economical and innovative method for the decontamination of packaged fresh foods (Yong et al., 2015; Ziuzina et al., 2015). Plasma jet, which provides a stable, homogeneous, and smooth discharge under atmospheric pressure without requiring high temperature and pressure, is highly preferred in the industrial field due to these features (Nehra et al., 2008). However, it shows limited effectiveness in applying to larger surfaces, unlike DBD (Bermúdez-Aguirre, 2019).

4.1.2 | Spinach

A study comparing continuous and static mode application of DBD for microbial decontamination of spinach reported that DBD applied in static mode resulted in a reduction of 1.7 log CFU/mL *L. innocua*, whereas continuous mode only caused 3.8 log CFU/mL decrease (Ziuzina et al., 2020). Compared to the static mode, the continuous mode may have dealt a more fatal blow to the ability of bacterial cells to repair and regenerate themselves (Wan et al., 2019). Indeed, Durek et al. (2022), when compared the continuous and static modes they found that microbial decontamination was more effective in the continuous mode than in the static mode, but they detected significant chlorophyll degradation in product color and significant changes in phenolic compounds. In another application with CP-generating paper-based electrodes made, it has been reported that for *E. coli* and *L. innocua*, 4.6 ± 0.6 and 4.8 ± 1.7 log CFU/spinach leaves of inhibition were observed, respectively (Wang et al., 2022). Researchers applying DBD plasma to baby spinach leaves reported a reduction of 3.77 and 3.18 log CFU/sample for *E. coli* O157:H7 and *Salmonella enterica* (Sudarsan & Keener, 2022). Microorganisms with catalase activity, such as *E. coli* O157:H7 and *S. enterica*, break down H_2O_2 into water and oxygen. With plasma application, it can lead to nitric and nitrous acid formation, resulting in a decrease in pH on the leaf surface and an increase in inactivation (Iwase et al., 2013; Misra et al., 2015). In a different study investigating the effect of aerosolized H_2O_2 on the quality and microbial decontamination of spinach, it has been reported that the effectiveness of aerosolized hydrogen peroxide depends on the type of inoculated bacteria, location, and product type, but it can also be used for sterilization purposes. This research reported that microbial reduction in spinach leaves was 1.5, 4.2, and 4.0 log CFU, respectively, for *E. coli* O157:H7, *S. typhimurium*, and *L. innocua* (Jiang et al., 2017). Earlier, Klockow and Keener (2008) reported a change of 0.1°C in temperature after DBD plasma application and an effective reduction in microbial load of packaged spinach within 5 min. Tan and Karve (2021) reported that the inhibition efficiency of DBD plasma active mist increased with the increase in the application time that inhibition in spinach leaves were 0.9 ± 0.1 and 2.0 ± 0.2 log CFU/g at 5 and 20 min, respectively.

4.1.3 | Other vegetables

Researchers investigating the inhibition efficiency by applying low-pressure plasma to radish sprouts have reported a reduction of 2.6 ± 0.4 log CFU/g in a population of *S. typhimurium* (Oh et al., 2017). Researchers applying SDBD to fresh-cut rocket leaf (Arugula) salad have reported that the inhibition for microorganisms changed to 1.020, 0.298, 0.996, and 0.493 after 10 min. Additionally, it is reported that inhibition seems to be less in *Pseudomonas* compared to others (Giannoglou et al., 2020). Dimitrakellis et al. (2021) applied DBD in a storage container; the initial microbial load of products from fresh-cut arugula leaves was reduced by 1.02 log CFU/g, and the shelf life of fresh-cut arugula leaves stored at 2°C was increased by 84%. A reduction of 1.8 ± 0.2 log CFU/g on *L. monocytogenes* has been achieved with the Weibull model (400 W, 10 min) in cabbage leaves treated with low-pressure plasma, and it was stated that microbial inactivation with low-pressure plasma varies depending on the gas (N_2, He + O_2) used and the other application conditions (Lee et al., 2015). In another study, in which UV-C and corona plasma were applied together, a 3.85 log CFU/cm^2 reduction was observed without being affected by the surface structure of vegetables (Srey et al., 2014). Applying plasma jet to cabbage leaves, the researchers reported a 5.5×10^3 CFU/mL reduction in *E. coli* O157:H7 after 300 s (Shah et al., 2019). Tan and Karve (2021) applied DBD plasma activated with mist on cabbage leaves and achieved the inhibition of around 0.8 ± 0.1 and 1.3 ± 0.1 CFU/g in *Enterobacter aerogenes* at 5 and 20 min, respectively.

4.2 | Effect of CP on FGLVs biocomponents

Plants rich in antioxidant content play an important role in the prevention of many diseases, such as cancer, cardiovascular diseases, hypertension, and stroke as a result of regular consumption (Zhou et al., 2021). Polyphenols (carotenoids, phenols, anthocyanidins, catechins, thiols, flavonoids, phytosterols, etc.) and especially vitamins C and E are the main phytochemicals that make up the total antioxidant content of a plant (Muanda et al., 2011; Muhammad et al., 2018). These plant compounds are thermally unstable and can be affected by physical and biochemical variables, such as pH, enzymes, and oxygen, during storage and processing. Researchers have been talking about a protective or curative effect, not reducing the direction of the existing polyphenol content or activity of CP. CP is important for the recycling of food waste and the extraction of functional polyphenols from these wastes (Cao et al., 2021). The effect and interaction of CP on the bioactive components of food are still unclear. Polyphenols such as anthocyanins can be released in the cell vacuole and out of the cell as a result of the cell membrane being broken down by the effect of CP (Figure 3). In this situation, it has been reported that polyphenol extraction will accelerate due to the faster penetration of solvents into the cell (Kobzev et al., 2013). A recent study has reported that CP increased the total phenol content, antioxidant capacity, total flavonoid, and anthocyanin accumulation by activating the gene expression of the released ROS (Ganesan et al., 2021). On the other hand, it has been reported that polymerization, which occurs at a high rate due to the increase in processing time in CP application, causes degradation in oligosaccharides and increases the sucrose content (Almeida et al., 2015; Rodríguez et al., 2017). In addition, as a result of plasma application changes in α-helix and β-conformations of proteins leading to denaturation have been stated (Pankaj et al., 2018). It has been reported that CP leads to a chemical reaction on allergens in the protein structure as a result of the cleavage of sulfur peptide bonds, the oxidation of amino acids, and the cross-linking of the plasma reactive species with peptide bonds (Ganesan et al., 2021). Vitamins, especially ascorbic acid, are another important quality criterion in FGLVs. Light, the presence of free radicals in the environment, interaction with heavy metals, and high or low-temperature cause vitamin loss (Martemucci et al., 2022). In a CP-treated FGLV, the amount of ascorbic acid may decrease as a result of the reaction of released ozone and other oxidizing plasma species (Kumar et al., 2022). In addition, the pre-treatments applied to the sample (cutting, shredding, etc.), the plasma time, and the type of gas selected are important parameters that reduce the amount of ascorbic acid (Muhammad et al., 2018). Reactive gases released by CP application have been reported to cause changes in pH and acidity values by interacting with moisture in foods on solid surfaces such as FGLV. Researchers think that the formation of acidic compounds occurring on the surface of the food is the result of the interaction of CP only with the moisture on the surface of the food. On the other hand, Oehmigen et al. (2010) reported that NO, which is a reactive species, will cause the formation of nitric acid, resulting in a decrease in pH.

4.3 | The effects of CP on the quality parameters of FGLVs

The preservation of the green and bright colors of the products is important as it provides information about the processing parameters and mostly determines consumer acceptance. Chlorophyll is chemically unstable in the presence of heat, light, and low pH, as well as enzymes such as O_2 and chlorophyllase, but ROS, RNS, and UV rays formed in the environment as a result of CP application can affect the stability of chlorophyll (Jurić et al.,). Color changes due to chlorophyll degradation in FGLVs are undesirable. But, the type of CP applied, parameter conditions, and post-application treatments can change the effect of CP on the product. In the literature, there are a limited number of studies evaluating the effect of CP application on the quality of FGLVs. In addition, there is not enough research in the literature to address and evaluate the sensory effect of CP on FGLVs in all its aspects. The gases used in CP, the composition of the gases, and the possible residue risk after application may have limited the sensory evaluation in terms of taste and flavor. Although the reliability of CP in terms of microbial decontamination and product sterilization has been accepted, surface disinfection is very important in sensory evaluation. Studies on FGLVs are insufficient to explain the interactions at the molecular level when CP's gas composition is evaluated in terms of product and packaging material. More research is needed to understand how CP affects the stability and reactivity of food ingredients. In Table 4, published reports investigating the effect of CP application on quality characteristics (color, pH, hardness, antioxidant change, etc.) of FGVLs are given in detail. Most studies on FGLVs reported that CP did not affect the color of FGLVs (Cui et al., 2018; Dimitrakellis et al., 2021; Fernandez et al., 2013; Giannoglou et al., 2020; Jahid et al., 2014, 2015; Jiang et al., 2017; Min et al., 2016, 2017; Oh

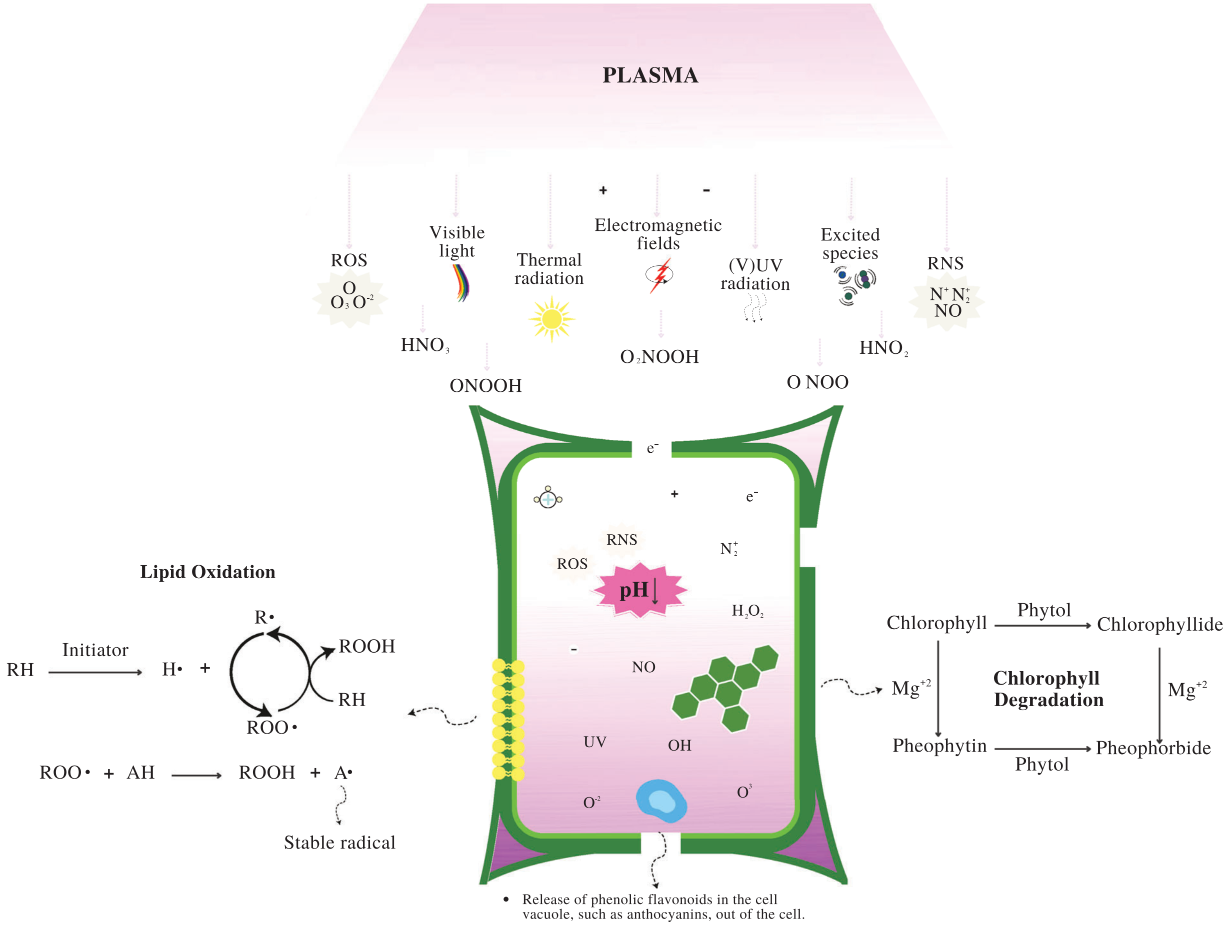

FIGURE 3 Effect of cold plasma technology on green leafy plant cells.

et al., 2017; Shah et al., 2019; Song et al., 2015; Srey et al., 2014; Ziuzina et al., 2020). Browning occurs especially as a result of tissue damage during storage and processing. The enzyme polyphenol oxidase (PPO) causes the formation of melanin pigments responsible for browning by oxidizing the phenolic compounds found in plants (Moon et al., 2020). In addition, other endogenous enzymes in food can cause various changes in the quality properties of foods during processing and shelf life (Han et al., 2016). CP is successful in maintaining pigment stability compared to other sterilization methods. However, as the application time increases, the pigment storage areas may be damaged, and accordingly, the oxidative degradation of the pigments may increase, and release out of the cell may occur (Amorim et al., 2023). For this reason, besides the applied CP type and process conditions, its interaction with the conformation of food enzymatic enzymes is also important. For instance, Jahid et al. (2014) reported that corona plasma did not affect the sensory evaluation of lettuce leaves and product color below <15°C. Kang et al. (2019) reported that CP parameters trigger the inactivation of the PPO enzyme under suitable conditions. In a recent study, Wang et al. (2022) reported that DBD plasma caused reddening on the surface, whereas the application did not cause tissue softening in spinach leaves. Earlier, Klockow and Keener (2008) reported that the application of DBD plasma caused negative effects on the color of packaged spinach. It has been reported that when Air-DBD is applied, the open areas of spinach leaves that are stored in the refrigerator for 24 h become yellowish, and the dark areas turn brownish–green. The researchers have reported that the negative effect on color was due to ozone, a reactive species formed after application. Similarly, although no color change was observed on the cut edges as a result of plasma jet application in Baby Kale (*Brassica oleracea*) leaves, which was divided into three parts, it was reported that browning or bleaching occurred as a result of 600 s CP applied to the whole leaf. Researchers have attributed this to the inactivation of the polyphenol oxidase enzyme found in the cut leaf margins as a result of CP application (Shah et al., 2019). In an earlier study where corona plasma and clove oil were applied together, it was reported that the a^* value of lettuce increased the result of CP radiation, but other quality parameters were not affected (Cui et al., 2016). In another study, it was reported that lettuce treated with corona plasma showed significant differences in color tone after 7 min (Bermúdez-Aguirre et al., 2013). Besides color, other quality parameters (pH, texture, color, shelf life, weight loss, aw, ascorbic acid concentration, antioxidant activity, etc.) were also studied in FGLVs. According to Jahid et al. (2015), corona plasma did not cause a significant change in the texture and sensory evaluation of the product in lettuce leaves. Different studies also reported that the application of DBD on bulk Romaine lettuce did not cause any significant changes in the sensory, metabolic properties, and other parameters of the product (Min et al., 2017). Other researchers investigating the synergistic effect of UV-C combined with corona plasma on bulk Romaine lettuce and cabbage samples also reported that texture was not affected by this process (Srey et al., 2014). Dimitrakellis et al. (2021) reported that DBD application to rocket leaves did not affect the quality parameters tested and increased the shelf life by 84%; however, the DBD applied to arugula salad did not affect the pH; the product hardness decreased as the application time and temperature increased (Giannoglou et al., 2020). Song et al. (2015) reported that low-pressure plasma application caused weight loss in lettuce leaves during storage, whereas there was no change in aw, color, ascorbic acid, antioxidant activity, and physicochemical properties. In another study on freshly cut radish sprouts, it was reported that low-pressure plasma application reduced moisture content and did not affect other parameters (Oh et al., 2017). A study by Cui et al. (2018) reported that there was a significant increase in the sensory evaluation of samples as a result of corona plasma application compared to control groups. In a study examining the effect of low-pressure plasma on secondary metabolites of Lamb's Lettuce (*Valerianella locusta*), it increased diosmetin content, a decrease in phenolic acid and pure monophenol, and faster degradation of flavonoids than phenolic acids, differences depend on the applied plasma voltage (Grzegorzewski et al., 2010). Researchers investigating how the nitrite, nitrate, pH, and peroxide values on the surface of baby spinach leaves reported acidity increases with the increase of the processing time while DBD plasma application caused a decrease in nitrite, nitrate, and peroxide values (Sudarsan & Keener, 2022). Min et al. (2016) reported that the color and weight of the product has not been affected after the DBD treatment in Romaine lettuce in the package. An insignificant increase in product temperature has been reported also.

5 | CONCLUSIONS

In this article, we presented the pros and cons of systems comparison, methodology, and system parameters to better understand the impact of CP applications on the microbial decontamination and quality characteristics of FGLVs. In doing so, in addition to the CP parameters, the complex structure of FGLVs, the food packaging material used, and the external environment were considered together. Although recent developments regarding the commercialization potential of CP-treated FGLVs are promising, there are some limitations. For FGLVs, other than the chemical application, the postharvest process application options are limited. In recent years, CP has been applied to many different foods to decontaminate microorganisms, such as bacteria, viruses, molds, and yeasts, which have disruptive effects. Plasma can be applied directly to the product in different packages and has great potential to be combined in hurdles with different technologies. The studies were mostly carried out in certain product groups and processing conditions and parameters change according to the selected product and the CP variety used, whereas these parameters are not reported in all studies. Before becoming accessible as a commercial application process, more work to be done to understand the technological effects of CP on the product and how CP interacts with the biological content of vegetables, and how and if the free radicals were released after this interaction. The primary reactive species released during plasma production would cause enzymatic changes and oxidation in vegetable products, especially those with high oil content. Although some negative effects have been reported in quality characteristics, it should be noted that these changes could have occurred depending on the applied plasma conditions (time, distance, frequency, voltage, gas, etc.). The other subject of discussion is the electrical energy required for plasma production and the gas source used for CP formation. From this perspective, the economic cost is to be considered to limit the use of CP on an industrial scale unless more economically feasible and sustainable CP production systems are developed. This review focused on the effect of plasma species directly produced by CP on FGLVs. Plasma-activated water or liquid applications, which are used indirectly as CP applications on FGLVs, were excluded from this review. Recent studies demonstrated that by exposing water or a sanitizing liquid to CP, antibacterial properties can be improved when plasma-activated water or a liquid is applied to FGLVs. More studies should be carried out to demonstrate the commercial viability of CP systems for vegetable processors.

AUTHOR CONTRIBUTIONS

Emel Özdemir: Conceptualization; data curation; formal analysis; visualization; writing—original draft; methodology; investigation; supervision; project administration; writing—review & editing; resources; funding acquisition; validation; software. **Pervin Başaran**: Conceptualization; data curation; formal analysis; visualization; writing—original draft; writing—review & editing; project administration; supervision; investigation; methodology; software; validation; funding acquisition; resources. **Sehban Kartal**: Conceptualization; data curation; formal analysis; visualization; writing—original draft; writing-review

& editing; project administration; supervision; investigation; methodology; software; validation; funding acquisition; resources. **Tamer Akan**: Conceptualization; data curation; formal analysis; visualization; writing—original draft; methodology; investigation; supervision; project administration; writing—review & editing; software; validation; funding acquisition; resources.

ACKNOWLEDGMENTS

This work was supported by the Scientific Research Projects Department of the Istanbul Technical University. Project Number: 43656. We would like to thank the Scientific Research Projects Department of the Istanbul Technical University.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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How to cite this article: Özdemir, E., Başaran, P., Kartal, S., & Akan, T. (2023). Cold plasma application to fresh green leafy vegetables: Impact on microbiology and product quality. *Comprehensive Reviews in Food Science and Food Safety*, 1–32. https://doi.org/10.1111/1541-4337.13231