Chapter 6
Agriculture and Food Processing Applications

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Abstract Non-thermal plasma produced at atmospheric or low pressure has the potential to solve problems in modern agriculture and the food industry and may specifically address challenges resulting from the current climate crisis and environmental changes. In laboratory conditions, non-thermal plasma has shown promising results in applications such as plant disease control, seed germination, plant growth, food sanitation, and improvement of food quality and functionality. In particular, the improvement of plant vitality under stress conditions and storage time suggests that plasma can play a pivotal role in sustainable agriculture and the food industry. Advances in field- and industrial-scale applications are currently underway, as reported by an increasing number of studies. In this chapter, we summarize and discuss studies on the application of low-and atmospheric-pressure plasma to agriculture and food production.

6.1 Background

The agriculture and food industries face many challenges, including some resulting from climate change and environmental pollution. Climatic change has caused the emergence of new diseases and changes in plant susceptibility to diseases [76]. Some estimate a 5–50% reduction in crop yield as a result of climatic change by 2100 [10]. Thus, climate change, sustainable agriculture, food preservation, and improved storage of fresh produce have become important issues to be resolved.

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Conventional approaches to solve problems in agriculture and food processing are mostly focused on the use of chemicals. However, chemical-based techniques have frequently shown their limitations with respect to safety and emergence of resistance. Alternative technologies may be needed to overcome these challenges.

Non-thermal plasma is a promising technology to solve problems in the agriculture and food industries. Although intensive studies of plasma application to agriculture and foods started relatively later compared to medical applications, enormous advances in knowledge and technical development have been made in the last decade. Non-thermal plasma generated under atmospheric, low, or medium pressure has been examined for its potential in food sanitation, food storage, plant disinfection, and enhancement of seed germination and growth [12, 36, 106, 187, 278]. Although most investigations have been performed under laboratory conditions, the application of plasma at industrial and field scales is currently increasing. This chapter presents a synthesis of studies performed on plasma applications in agriculture and food production. We attempted to include as many studies as possible, and any omissions were unintentional.

6.2 Application of Non-thermal Atmospheric Pressure Plasma to Prevent Seed Borne Infections

6.2.1 General Treatment of Seeds

Seed is a basic and vital input for agricultural productivity considering that ninety percent of food crops are grown from seed. To guarantee health and quality (maximum germination above 80%) of seeds, they are generally subjected to preharvest manipulation directed towards improving germination and to deliver protection against pathogens and related pests and diseases. Factors that can impair seed quality are related to: biological factors (pathological, entomological, animal grub); physiological factors (physiological disorders, nutritional imbalances, maturity); environmental/cultural factors (e.g. climate, weather, soils, water relations, light intensity); mechanical damage during processing; extraneous matter (growing medium, vegetable matter, chemical residues); and genetic variation and aberrations [148]. The chosen seed treatment should be functional across a wide variety of soil types, cultural practices and environmental conditions. They aim at changing physical form to facilitate sowing (pelleting), enhance germination by improving physiological performance (priming) and extend longevity by removing pathogens. Commonly applied modes of seed treatment can be categorized into: (1) mechanical methods (scarification, separation from infectious agents), (2) physical methods (electron beam treatment, hot water treatment: dry heat treatment: aerated heat treatment, radiation treatment, microwave, ultrasound), (3) biological methods (treatment with beneficial microorganisms including fungi and bacteria e.g. species of *Trichoderma*, *Pseudomonas*, *Bacillus*, *Rhizobia*), and (4) chemical methods (organic or inorganic,

metallic or non-metallic, insecticides, fungicides, bactericides using coating to form pellets or entrustments). Methods can also be combined to ensure pathogen inactivation, next to addition of auxiliary materials like nutrients or other growth promoting agents. In the past years, the application of chemical seed dressing has declined due to suspected negative effects on diversity of organisms agricultural landscapes [102, 261]. Growing concerns has led to a banned of most insecticides in the European Union, as well as chemical seed dressing using the agent Thiram (TMTD), widely applied as a fungicide in rape and leguminous seed treatment to prevent soil-borne infections [52].

Application of alternative non-chemical seed treatment methods are propagated, like electron beam treatment or are under development like cold plasma application in pre-harvest. Most non-chemical alternatives are not functional against soil borne pathogens or insect or animal grub, because no long-lasting reservoir of agents is formed. Commonly found soil borne pathogens, which often can also be spread by invested seeds, include the fungal genus *Fusarium, Pythium, Rhizoctonia, Phytophthora, Verticillium, Rhizopus, Thielaviopsis*, and *Sclerotia* [235]. In addition to being soil borne, some pathogenic bacteria like *Ralstonia solanacearum*, *Streptomyces scabies, Clavibacter michiganensis* subsp. *sepedonicum, Pectobacterium* spp., *Dickeya* spp., *and Agrobacterium tumefaciens* are also transmitted through infected planting materials such as tubers and cuttings. Some soil borne viruses, such as Tomato mosaic virus (tomato), Tobacco ringspot virus (tobacco), and Indian peanut clump virus can also be transmitted by nematode vectors or via infected seeds [235].

Nevertheless, the major strength of non-chemical methods lies in the prevention of seed borne infection originating from surface, or near surface attached pathogens. Currently, there are 213 annotated seeds borne pathogens according to the ISTA Pest list [11], encompassing fungi, bacteria and viruses. Commercially relevant examples are *Fusarium* causing a number of diseases in various plants (head blight in barley and panama disease of banana), *Tilletia* causing common bunt, dwarf bunt and stinking smut of cereals, *Ustilago tritici* causing common and loose smut in barley and rye, *Phoma* causing stem rot in rapeseed, *Typhula incarnata* causing snow mold in rye, and *Pyrenophora graminea/Drechslera tritici-repentis*, causing yellow leaf spot in wheat and barley.

Apart from the localisation of the pathogen on or inside the seed, the complex lifestyle with sexual and asexual cycles of especially fungi makes seed treatment more complicated. Reproduction of fungi is primarily by means of spores which can be produced sexually or asexually. The sexual reproduction cycle (teleomorphic phase) of fungi forms different types of spores via meiosis such as oospores, zygospores, ascospores and basidiospores. In the asexual cycle (anamorphic phase) oidia (formed by fragmentation of hyphae into individual cells), conidia (borne on tips or sides of specialized branches of hyphae) and sporangiospores (a nonmotile spore born in a sporangim or case) are produced by mitosis [2]. The disease cycle of monocyclic fungi usually starts with a primary infection, which involves colonization, growth, and reproduction as well as overseasoning in the absence of the host. Polycyclic fungi on the other hand, produce asexual spores (secondary inoculum) at each infection

site that can cause new (secondary) infections to produce more asexual spores for more infections.

In vegetables and herbs, bacterial and viral pathogens are of special concern. Bacterial wilt in tomato caused by *Clavibacter michiganensis, Xanthomonas* causing citrus canker, bacterial leaf spot in many plant species, black rot of crucifers and bacterial blight of rice, *Pseudomonas syringae* causing wilt and spot diseases in many vegetables and legumes are frequently reappearing. Viral pathogens in vegetables and herbs encompass the mosaic virus (TMV, ToMV), Asparagus Virus (AV-2), tobacco ringspot virus (TRSV) and pea early browning virus (PEBV): The efficiency of cold plasma in reducing seed associated pathogens will be discussed in the following Sects. 6.2.2, 6.2.3 and 6.2.4. Not considered in this chapter are losses in seed quality and health caused by nematodes, insects, herbivory, nor post-harvest disease, which will be handled in Sect. 6.4. Notably, almost every study on CAP inactivation of pathogens is unique because they either use a specific plasma source, often build in-house, with specific configurations (e.g., input power, working gas, treatment time), they deal with treatment of different matrices (e.g., suspensions in water, other solutions, seeds from different plant families) and different type of pathogens (fungi of different life cycle stages, bacteria in sporulated or vegetative form, viruses) are used. This diversity makes it difficult to compare results from different studies directly and to define any universal inactivation parameters.

6.2.2 Effect of Cold Plasma Treatment on Fungi

Because of their relevance for losses in crop yield, fungal pathogens have been subjected to a number of studies, 39 are listed in Table 6.1. Inactivation of is highly dependent on the treatment properties, and the optimal parameters need to be chosen on a case-by-case basis.

Studies, which can serve as a general proof of concept for inactivation of fungal pathogens, are using spore suspensions as a test object. In these cases, the complex matrix of seed surfaces including topography, texture and chemical composition are absent. Moreover, information on the effect of the individual CAP treatment on seed germination is lacking, which makes it difficult to transfer gained knowledge to actual occurring crop diseases. However, 12 studies demonstrated efficient inactivation of *Alternaria, Ascochyta Aspergillus, Chaetomium, Cladosporium, Colletotrichum, Fusarium (Gibberella Penicillium,), Phomopsis* and *Rhizoctonia.* Reduction was in the range 44% to complete inactivation [13, 127, 143, 146, 193, 232, 243, 250, 252, 254, 316, 320, 360]. A variety of plasma sources was used including DBD in three cases, jets in two, corona, and arc discharge in three cases, microwave induced, and radiofrequency CAP was applied in two cases each.

Several authors used artificial inoculated seeds to investigate the inactivation efficiency of CAP. Important for pre-harvest application is an unimpaired seed germination, making it necessary to at least monitor maximum germination for the respective plasma treatment. Unfortunately, this was not always the case, but

Table 6.1 Efficiency of non-thermal plasma treatment for inactivation of fungal pathogens in pre-harvest

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Fungal sporesuspension on agar-coated microscope slides	*Ascochyta pinodella, fusarium culmorum*	Atmospheric pressure dielectric barrier discharge (DBD)	Air, 60, 180, 360 s	After 180 s delay in growth, complete inactivation after 360 s	[13]
Fungal sporesuspension	*Penicillium digitatum*	High-density nonequilibrium atmospheric pressure plasma	Oxygen/argon, 1–6 min	At 0.6% flow rate ratio = in each case1 log unit decrease from 1 to 4 min and 3 log units decrease at 5 min	[127]
Fungal sporesuspension on VM (Vogel's Minimal) agar plate	*Fusarium graminearum, fusarium oxysporum*	Microwave plasmajet	Mixtures of argon with oxygen (5:1), with nitrogen(5:1), or with air (5:1), and nitrogen gas, 3 slm, 10–180 s	After 1 min plasma treatment, hyphal growth in *N. crassa* and *F. oxysporum* no growth in *F. graminearum*	[232]
Fungal sporesuspension inserted by spraying	*Aspergillus niger, penicillun citrinum*	Atmospheric pressure plasma	Air, 1–5 h	99.9% inactivation after 5 h	[243]
Fungal sporesuspension in PBS or saline (0.85% NaCl) solution	*Fusarium oxysporum f.sp. lycopersici*	Atmospheric pressure dielectric barrier discharge DBD	Air or argon, 1, 5, 10 min	Spores in saline solution reduced germination only at 10 min treatment after 3 h post treatment, germination of spores in PBS or air plasma not affected	[250]
Fungal spore suspension	*Colletotrichum gloeosporioide*	Plasma-activated water, atmospheric pressure corona discharge	Artificial air (21% oxygen + 79% nitrogen) or bottle oxygen (99.99%), 2.5 slm, plasma treatment time 5–30 min, PAW exposure time 10 and 30 min	Inactivation rate 10 min exposure = 44% and 85% for Air and O_2 plasma 30 min exposure 4–45% for air and O_2 plasma	[360]

(continued)

Table 6.1 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Fungal spore suspension in sterile physiological saline solution	*Penicillium crustosum* (DBM 4159) *Aspergillus oryzae* (DBM 4002) *Cladosporium sphaerospermum* (DBM 4282) *Alternaria* sp. (DBM 4004)	Corona discharge, negative and positive discharge	Air, 5–30 min	*Penicillium*: reduction up to 2 log units for 5–20 min treatment time, after 25 min complete inactivation (positive discharge), no reduction for negative discharge *Aspergillus*: up to 20 min no reduction, 30 min 3 log units reduction for positive discharge, reduction of 2 log units for 20 min treatment time for negative discharge *Cladosporium*: positive and negative discharge reduction by 4–5 log units for the first 20 min, complete inactivation >20 min *Alternaria*: complete reduction form 15 min treatment time on for negative and positive discharge	[320]
Fungal spore suspension in water, Spores on rice (*Oryza sativa* L. cv. Hopyeong) seeds submerged in water	Inoculated with *Fusarium fujikuroi*	Arc discharge Plasma	Air, Suspension 1, 5, 10 min, Seeds 5, 10, 20, and 30 min	Spore suspension: maximum reduction by 3.4 log units at 10 min reduction in infected seeds by 20% up to 10 min treatment time, 80% for >10 min treatment time No seed germination determined	[146]
Fungal spore suspension on potato dextrose agar (PDA) Spores on rice (*Oryza sativa* L. cv. Cocodrie) seeds	Inoculated with *Gibberella* (i.e. *Fusarium*) *fujikuroi* isolate, FGSC #8381	Atmospheric pressure dielectric barrier discharge DBD	Air, 0.5, 1, 2, or 3 min	Linear increase in clearing zone form 10–180 s Reduction of spores on seeds by 80% after 1 min No decrease in seedling emergence	[143]

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Table 6.1 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Fungal spores on filter paper	*Cladosporium sladosporioides*, *Penicillium citrinum* *Chaetomium sp.*	Microwave-induced argon plasma	Argon 100 L per min, 1–30 s	Complete inactivation at 1 s treatment time	[254]
Fungal spores on filter paper or slide glasses coated with poly-L-lysine	*Aspergillus niger Penicillium citrinum*	Microwave-induced argon plasma	Argon 100L per min, 1–30 s	Complete inactivation at 1 s treatment time	[252]
Fungal spores suspension dried on glass plate Spores on tomato seeds (*Solanum lycopersicum* L.)	Inoculated with *Cladosporium fulvum*	Atmospheric pressure plasma jet	Oxygen/argon(volume ratio: 1/99) feed gas, 10–300 s	Inactivation of spores efficient from 11 kV input voltage onwards and 50 s treatment time From 20 to 60 s treatment time decrease in rotting rate of tomato plants by 15% No seed germination determined	[193]
Seeds and plants of winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), narrow-leaved lupine (*Lupinus angustifolius* L.)	Inoculated with *Fusarium culmorum* on winter wheat, naturally occurring *Alternaria* sp., *Cladosporium* sp., *Colletotrichum gloeosporioides*, Kabatiella caulivora,	Low-pressure radio frequency plasma	Air at a pressure of 200 Pa., 2, 5, 7 min, vacuum control	Maize: reduction in infection with *Penicillium* spp. by 21%, no reduction in *Fusarium* Lupine: no *Colletotrichum* and *Kabatiella* detected after treatment, reduction in infection level by *Alternaria* by 30% and *Cladosporium* by 60% Winter wheat: *Fusarium* no significant reduction, *Alternaria* infection reduced by 25–35% No decrease in seed germination	[84]
Seeds of barley (*Hordeum vulgare* L. cultivar Tokak 157/37), corn (*Zea mays everta* L.)	Natural fungal load	Low pressure ambient air plasma, 15 Pa	Air, 2–20 min	No effect from 2 to 5 min, decrease by max. 25% at 20 min treatment time in barley, reductions by 40% at 10 min treatment time in corn seeds No decrease in germination of seeds	[37]

(continued)

Table 6.1 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of barley, (*Hordeum vulgare* L.) wheat (*Triticum aestivum* L.)	Natural fungal load, barley seeds inoculated with *Penicillium verrucosum*	Atmospheric pressure dielectric barrier discharge DBD plasma	Air, 5, 20 min direct and indirect treatment	Barley: 20 min treatment time: natural load reduction by 2.1 and 1.5 log units for direct and indirect treatment, *P. verrucosum* reduction by 3.6 and 2.7 log units for direct and indirect treatment respectively, seed germination: not determined Wheat: 20 min treatment time: reduction of natural load by 2.5 and 1.7 log units for direct and indirect treatment, seed germination: significant decrease	[189]
Seeds of broccoli (*Brassica oleracea* var. kialica plen)	Natural fungal load (moulds, yeasts)	Corona dischargeplasma jet	Air, 1, 2, 3 min	Reduction of moulds and yeasts by ~1 log unit and 1.5 log units at 2 and 3 min treatment time respectively Decrease in seed germination at 3 min treatment time by 32%	[157]
Seeds of buckwheat CB (*Fagopyrum esculentum* Moench) and TB (*Fagopyrum tataricum* Gaertn.)	Natural fungal load	Radiofrequency (RF) plasma system 1 Pa	Oxygen gas with 202 standard cm^3 min^{-1}, 15, 30, 45, 60, 90, and 120 s	Identification using next generation sequencing, *Alternaria, Didymella (Phoma), Epiccocum, Rhodotorula, Hannaella* Reduction in fungal cover of petri dish by 13% for 15–30 s treatment time and by 20–40% for treatment times >30 s in CB No reduction up o 90 s in TB, reduction by 30% at 120 s treatment time Decrease in seed germination by ~10% from 15 to 45 s and by 50% at treatment times >45 s	[228]

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Table 6.1 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of chinese cabbage (*Brassica campestris* var. amplexicaulis)	Inoculated with *Rhizoctonia solani*	Atmospheric- and low-pressure plasma	Argon 0.5 L/min, 2–40 min	Survival rate decreased from 100 to 3% from 5 min treatment time onwards Strong delay in seed germination by 64%	[241]
Seeds of common bean (*Phaseolus vulgaris* L.) cultivar SCS204	Natural fungal load	Atmospheric pressure dieletric barrier discharge DBD	Gas not defined, 10–30 min exposure	Natural community identified as *Aspergillus* sp. and *Penicillium* sp. by selective plating and visual determination Complete inactivation after 10–30 min treatment time Seed germination as visual radicle formation, no radical formation at 20, 30 min, inferior development at 10 min	[286]
Seeds of cucumber (*Cucumis sativus* L.), pepper (*Capsicum annuum* L.)	Inoculated with *Didymella bryoniae, cladosporium cucumerinum, Didymella licopersici*	Diffuse coplanar surface barrier discharge (DCSBD)	Air, Cucumber 40 s, Pepper 4 s	Cucumber: complete reduction of *C. cucumerinum*, reduction of *D. bryoniae* spores 60–80%, Pepper: reduction of *D. licopersici* spores from 50 to 80% No decrease in seed germination	[325]
Seeds of ginseng (*Panax ginseng*)	Natural fungal load	Atmospheric pressure dielectric barrier discharge- planar-type DBD	Argon and Argon/oxygen mixture (80:20); 10 min each day, 3 days in a row	Identification using next generation sequencing: *Coniochaeta, pyrenochaeta, humicola, clonostachys, fusarium, mortierella* No reduction in *Humicola*, *Clonostachys*, reduction below 20% in *Fusarium* and *Mortierella*, reduction by >80% in *Coniochaeta* and *Pyrenochaeta*, Survival of fungi decreased to 40% in Argon/oxygen mixture No decrease in seed germination	[174]

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Table 6.1 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of hazelnut (*Corylus avellane*), peanut (*Arachis hypogaea*), pistachio nut (*Pistacia vera*)	Inoculated with *Aspergillus parasiticus*	Low pressure cold plasma (500 m Torr)	Air gas and Sulfur hexafluoride; 1–20 min	Air plasma 1-log reduction SF6 plasma ~5-log decrease (in 5 min) No seed germination determined	[25]
Seeds of hazelnuts (*Corylus avellane*)	Inoculated with *Aspergillus. flavus* (ATCC 327) and *Aspergillus parasiticus* (ATCC 1041)	Atmospheric pressure fluidized bed plasma	Air and nitrogen, 2–20 min	Maximum reductions of 4.5 log for *A. flavus* and 4.2 log units for *A. parasiticus* after 5 min treatments in nitrogen plasma No seed treatment determined	[57]
Seeds of hazelnuts (*Corylus avellane*)	Natural fungal load and inoculated with *Aspergillus flavus* and *A. parasiticus*	Atmospheric pressure fluidized bed plasma	Air and nitrogen; 1–5 min	Reduction in *A. flavus* by (4.2 log) and *A. parasiticus* (4.1 log) after 5 min treatment, reduction in natural load by 3.45 log units at 2 min, no seed germination determined	[58]
Seeds of lentil (*Lens culinaris*)	Inoculated with *Aspergillus niger, Penicillium decumbens*	Diffuse Coplanar Surface Barrier Discharge	Air, 3, 5, 10 min	*P. decumbens*. maximum reduction of 3.1 log CFU/g after 10 min treatment, *A. niger* 1.6 log CFU/g after 10 min, seed germination: 120 s treatment time 90%, 180 s treatment time 42%, 240 s treatment time 5% germination	[356]
Seeds of maize (*Zea mays* L.)	Natural fungal load	Gliding Arc, spatial post-discharge mode	Air, 300, 900 s	Reduction in infection degree by ~48% at 300 s treatment time No decrease in seed germination	[145]
Seeds of maize (*Zea mays* L.)	Natural fungal load and inoculated with *Aspergillus flavus, Alternaria alter-nata, Fusarium culmorum*	Diffuse Coplanar surface barrier discharge AP DCSBD CP	Air; 60–300 s	Reduction by 3.79 log (CFU/g) in *F. culmorum* after a 60 s plasma treatment, 4.21 log (CFU/g) in *A. flavus* and 3.22 log (CFU/g) in *A. alternata* after a 300 s plasma Decrease in seed germination from 180 s onwards	[380]

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Table 6.1 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of narrow-leaved lupine *(Lupinus angustifolius* L.)	Natural infected seeds with *Fusarium* sp., *Stemphilium* sp., *Colletotrichum/Glomerella, Didymella pinodes* (syn. *Mycosphaerella pinodes*)	Radiofrequency (RF) capacitively coupled discharge	Air, 5, 10, 15 and 20 min	Maximal reduction of fungal infection in lupine at 15 min treatment time 16% for *Fusarium* sp. 14% for *Didymella pinodes,* 10% for *Stemphilium* sp., no reduction in *Colletotrichum/Glomerella* No decrease in field emergence at 15 min treatment time, decrease by ~7% at 20 min	[81]
Seeds of narrow-leaved lupine (*Lupinus angustifolius*), field pea (*Pisum arvense*)	Natural fungal load	Radiofrequency (RF) capacitively coupled discharge	Air, 5, 10, 15 and 20 min	Fungi were identified via morphological and cultural characteristics = *blue* lupin infected mainly with *Fusarium* and *Alternaria*, seeds of field pea with *Fusarium*, *Alternaria* and *Stemphilium* Field pea: maximum reduction of fungal infection at 10 min treatment time by 4%, 24 and 3% for *Fusarium*, *Alternaria* and *Stemphylium* respectively Lupine: maximum reduction at 15 min treatment time by ~9% and 1% for *Fusarium* and *Alternaria* respectively Seed germination in lab field pea no decrease till 15 min, lupine decrease by 1% at 15 min	[82]
Seeds of pea (*Pisum sativum* L.) Zuccini (*Cucurbita pepo* L.)	Natural fungal load	Fluorinated silicate glass (FSG) plasma	Air (5 L/min), 30, 60 s	No identification of natural load Reduction by 1 and 3 log units for both species after 30 and 60 s treatment time, respectively No decrease in seed germination	[151]

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Table 6.1 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of pine (*Pinus radiata*)	Inoculated with *Fusarium circi-natum* (pine pest)	Diffuse coplanar surface barrier discharge AP DCSBD CP	Air; 5–300 s	Reduction of seed-borne pathogens (14–100%) Decrease in seed germination by 9–10% for 5 and 10 s treatment time No seed germination for treatment times > 60 s	[307]
Seeds of rapeseed (*Brasica napus*)	Natural fungal load (molds and yeasts)	Corona discharge plasma jet	Air, 1, 2, 3 min	Reduction by 2 log units at 3 min treatment Decrease in seed germination by ~ 30% at 3 min treatment time	[270]
Seeds of rice (*Oryza sativa* var. Indica cv. KDML105)	Natural fungal load	Atmospheric hybrid micro corona discharge plasma	Argon ~2.5 l/min, 5,10,15,20 min	Qualitative assessment reduced number of seeds with fungal infection, no quantification nor identification, visually, no fungal growth detected after treatment No decrease in seed germination	[150]
Seeds of soybean (*Glycine max* L.) variety DM 53i53 IPRO	Naturally infected seeds with *Diaporthe/Phomopsis* complex	Atmospheric pressure dielectric barrier discharge DBD	Oxygen/nitrogen mixture 6 NL/min, 60–180 s	Reduction in D/P infected seeds from 15% to minimum of 4% at treatment TN1 No decrease in seed germination	[264]
Seeds of sweet basil (*Ocimum basilicum*)	Natural fungal load	Atmospheric pressure surface dielectric barrier discharge (SDBD)	Humid air 7 slm; 10 to 600 s	Decrease of contaminated seeds by up to 35% at 300 s treatment time No adverse effect on seed germination	[7]
Seeds of wheat (*Triticum aestivum*)	Natural fungal load and inoculated with *Fusarium nivale, Trichothecium roseum, Aspergillus. flavus, Trichothecium roseum*	Diffuse coplanar surface barrier discharge AP DCSBD CP	Air; 10–600 s for NO microflora 1–300 s for AI fungi-infected seeds	Complete inactivation of naturally occurring filamentous fungi after 120 s treatment, complete inactivation of *Fusarium* after 90 s treatment time, *Aspergillus* after 240 s and *Trichothecium* after 180 s Decrease in seed germination from 70 s treatment time onwards	[379]

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Table 6.1 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of wheat (*Triticum durum*), bean (*Phaseolus vulgaris*), chick pea (*Cicer arietinum* L.), soy bean (*Glycine max* cv), barley (*Hordeum vulgare* L. cv.), oat (*Avena sativa*), rye (*Secale cereale*), lentil (*Lens culinaris*), corn (*Zea Mays*)	Inoculated with *Penicillum* sp MS1982 on wheat, *Aspergillus* sp. 798 on all	Low pressure cold plasma, 500 m Torr	Air and Sulfur hexafluoride, 30 s to 30 min	Log reduction of *Penicillum* sp on wheat maximum 3 and 2 log units at 20 min treatment for air and SF6 gas, respectively Log reduction of *Aspergillus* sp. for SF6: Wheat 2.6, Balrey 1.5, Oat 1.2, Lentil 0.8, Rye 0.6, Corn 0.5, Chickpea 0.5 No significant difference in germination treated with 5, 10, 15 min of air and SF6 plasma	[301]
Seeds of wheat (*Triticum vulgare* L.; cv. "Forhand"), barley seeds (*Hordeum vulgare* L.; cv. "Maltz")	Inoculated with *Fusarium culmorum* (CCM F-163)	Diffuse coplanar surface barrier discharge (DCSBD)	Air, 15–300 s	Wheat and barley: reduction at 30 s = 50%, 100% reduction after 120/180 s treatment time Seed germination: 60 s treatment decrease in max. germination by 30%, from 120 s plasma treatment onwards inhibition of germination by up to 54%., strong decrease in seedling vigor by up to 80%	[117]
Seeds of winter wheat (*Triticum aestivum*)	Natural fungal load	Packed bed reactor	Air, 3, 10, 30 s	Reduction of fungal colonies on wheat grains by 77% at the optimum exposure 10 s No decrease in seed germination	[161]
Spore suspension in sterile water	*Aspergillus flavus* hyphae	Diffuse coplanar surface barrier discharge AP DCSBD CP	Air, 5–180 s	Almost complete loss of cell viability from 30 s treatment onwards	[316]

needs to be addressed in future studies. Fungal pathogens investigated belonged to the genus *Alternaria, Aspergillus, Cladosporium, Colletotrichum (*syn. *Glomerella), Didymella (*syn. *Mycosphaerella), Kabatiella, Penicillium Rhizoctonia, Stemphilium, Trichothecium.* Studies with no simultaneous determination of seed published inactivation of pathogens from 1 to 5 log units for *Aspergillus* [25, 56, 58], by ~3 log units for *Penicillium* on barley seeds [189], a reduction in *Fusarium* infected seeds by 20–80% [146], or a significant decreases in *Cladosporium* diseased plants [193]. No decrease in seed germination was detected in four studies using artificial inoculated pathogens and subsequent CAP treatment. Efficiency of inactivation was depended upon the pathogen used with no effect for *Fusarium* inoculated on maize seeds [84], 0.5–3 log units for *Penicillum* and *Aspergillus* [301], 80% reduction of viable spores of *Fusarium* on rice seeds [143], up to complete inactivation of *Cladosporium* on cucumber seeds [325].

On the other hand, significant decrease in seed germination after CAP treatment was reported by seven studies. Efficiency of CAP treatment again depended on the pathogen used, along with plasma source and applied parameter including treatment time. Effects ranged from no effect for *Colletotrichum/Glomerella* along with rather small reduction in seed germination <10% [81]. A reduction by 3 to 4 log units for *Aspergillus*, *Alternaria* and *Fusarium* on wheat seeds up to complete inactivation using the same plasma source for *Fusarium*, *Trichothecium* and *Aspergillus* on maize seeds which was accompanied by severe decrease in seed germination for longer treatment times in both cases [379, 380]. A delay in seed germination >50% for Chinese cabbage accompanied by nearly complete inactivation of *Rhizoctonia* [241]. Seed germination of wheat and barley was decreased by ~54% for treatment times >120 s, while at the same time DBD treatment led to a nearly complete reduction of *Fusarium* [117]. Lentil seed germination decreased by 95% after treatment time of 240 s with a coplanar DBD, at the same time reducing viability of *Penicillium* and *Aspergillus* by 3 and 1.6 log units/g seeds, respectively [356]. Additionally, a complete loss of pine seed germination for coplanar DBD treatment >60 s was detected, while a complete inactivation of *Fusarium* was observed [307].

However, 18 studies dealt with natural fungal communities on seeds (often accompanied by artificial inoculation with specific fungi), which includes also non-pathogenic fungi. Two studies specifically focused on natural occurring pathogens like *Diaporthe/Phomopsis* complex on seeds of soybean [264] and *Fusarium sp., Stemphilium sp., Colletotrichum/Glomerella, Didymella pinode* on seeds of narrow-leaved lupine [81]. Pérez Pizá and colleges [264] published reduction in *Diaporthe/Phomopsis* infected soybean seeds from 15% to minimum of 4% after DBD treatment with no decrease in seed germination. Moreover, Filatova and colleges [81] reported the efficacy of at 15 min treatment of lupine seeds using a radiofrequency (RF) capacitively coupled discharge with maximal reduction of 16% for *Fusarium*, 14% for *Didymella*, 10% for *Stemphilium* and no reduction of *Colletotrichum/Glomerella.* At the same time, CAP treatment did not decrease field emergence at 15 min treatment time, while 20 min treatment resulted in a decrease by ~7%. Four publications dealing with natural fungal communities present a detailed identification applying selective plating and visual determination methods or next generation sequencing. The first one

by Filatova and colleges [82] identified fungi on lupine and pea seeds using morphological and cultural characteristics. Fungi on lupine consisted mainly of *Fusarium* and *Alternaria*, while on seeds of field pea *Fusarium*, *Alternaria* and *Stemphilium* were identified, using cultring techniques, which are selective and don't include the whole community. Moreover, inactivation using 10 min treatment of a radiofrequency capacitively coupled discharge displayed a maximum reduction of 4%, 24% and 3% for *Fusarium*, *Alternaria* and *Stemphylium* on pea seeds respectively. On lupine seeds, maximum reduction occurred at 15 min treatment time resulting in ~9% and 1% for *Fusarium* and *Alternaria* respectively. Seed germination in the laboratory resulted in no decrease until 15 min CAP treatment for field pea and a decrease by 1% at 15 min for lupine seeds. The second study using selective plating identified mainly *Aspergillus* and *Penicillium* on seeds of common bean [286]. Treatment applying DBD for 10–30 min revealed complete inactivation of both genera detected. However, seed germination presented as visual radicle formation resulted in a complete loss of radical formation at 20 and 30 min CAP treatment and in an inferior radicle development at 10 min treatment time. Two further studies implemented next generation sequencing to disentangle the fugal community. Lee and colleges [174] focused on ginseng seeds, detecting the following genus *Coniochaeta, Pyrenochaeta, Humicola, Clonostachys, Fusarium, Mortierella.* Treatment using DBD for 10 min three days in a row showed no reduction in *Humicola* and *Clonostachys*, a reduction below 20% in *Fusarium* and *Mortierella* and a reduction by >80% in *Coniochaeta* and *Pyrenochaeta* in an Argon/oxygen mixture. Additionally, no decrease in seed germination was observed. Likewise, next generation sequencing, as well as plating and visual identification were applied by Mravlje et al. [229] on the fungal community of buckwheat seeds. *Alternaria, Didymella (Phoma), Epiccocum, Rhodotorula* and *Hannaella* were identified. A radiofrequency plasma system operated at low pressure of 1 Pa was implemented and treatment times were in the range of seconds. After 120 s treatment, filamentous fungi of the genus *Alternaria* predominated, while other genus was detected in lower quantities. Alongside, seed germination decreased by ~10% from 15 to 45 s and by 50% at treatment times >45 s. No in-depth identification of the natural fungal load was presented in 12 other studies, displaying inactivation efficacy on barley, broccoli, sweet basil, hazelnut, maize, pea, rapseed, rice, soybean, wheat as a bulk parameter. Inactivation was in the range of 10% to 3 log units (99,99%) inactivation [7, 37, 58, 145, 150, 151, 157, 161, 189, 271, 379, 380]. Differences in the susceptibility of fungi to CAP compared to bacteria were previously reported with fungi being more resistant to CAP exposure [174, 189, 270, 380]. Nevertheless, the proposed mechanism of inactivation of filamentous fungi by CAP likely resemble the ones described in bacteria (see Sect. 6.2.3).

The plasma-treated fungal spores often show severe morphological degeneration including damage of cell envelope structures [252] also related to lipoperoxidation of cell macromolecules [316] and seem to undergo necrotic death [250]. Panngom and colleges [250] argued that elevated levels of peroxynitrite and nitrite originating from the CAP treatment of the saline solution might have been responsible for the observed fungal spore death. Furthermore, when direct CAP treatment is applied inactivation can occur via different other mechanisms e.g. DNA fragmentation or

destruction by UV irradiation, erosion through intrinsic photodesorption or erosion through etching to form volatile compounds as a result of slow combustion using oxygen atoms or radicals emanating from the plasma (reviewed by [165, 217, 218, 228]). As noted before, CAP produces different reactive species (RONS, e.g. atomic oxygen (O), metastable oxygen $\left(O_2^*\right)$, superoxide $\left(\cdot O_2^-\right)$, ozone (O_3), hydroxyl radical (·OH), hydrogen peroxide (H_2O_2), nitride oxide (NO), and nitride dioxide ($\cdot NO_2$)), which play a crucial role in the inactivation of any microbial target by oxidation of cytoplasmic membrane, protein and DNA [229]. Most likely, O and ·OH induces the largest number of hydrogen abstraction reactions [55, 364], while the activity of HO_2 and H_2O_2 is lower, however, the number of main chain and branched chain fractures of cell wall glucan structures appears to be bigger. Consequently, the destructive effect of H_2O and H_2O_2 is more efficient [55]. Fungi might exhibit possible protection from CAP damage when carotene pigments are present protecting spores from oxidative damage by plasma [232].

6.2.3 Effect of Plasma Treatment on Bacteria

Inactivation of bacterial pathogens, like fungal ones, is highly dependent on plasma source, configuration, and the treatment properties. The majority of studies applied DBDs for direct treatment or gliding arc for indirect treatment by producing plasma treated water or gas (Table 6.2). There are several proof of concept studies using spore suspension of phytopathogenic bacteria (e.g., *Xanthomonas campestris*, *Erwinia* sp., *Clavibacter michiganensis*, *Pectobacterium carotovorum)* showing a successful reduction in the number of viable bacteria from 1.5 log units to complete inactivation in a time-dependent manner [223, 224, 227, 230, 344].

There is an almost equal part of studies dealing with pathogens artificially inoculated on seeds or growth solution and naturally load on seeds with the majority applying DBD plasma sources or jets. Artificial inoculation of hydroponic growth solution for tomato cultivation with the pathogenic bacteria *Ralstonia solanacearum* and subsequent treatment of this solution using a gas-liquid phase discharge plasma reactor displayed a reduction by 5 log units in the solution and a decrease in disease severity of tomato seedlings by 80% after 10 days of growth [247]. Treating tomato seeds with a capacitively coupled plasma (CCP) generated by a radiofrequency discharge at 150 Pa led to an increased resistance of the 30 days old plants to *Ralstonia solanacearum* by 25% [140]. Treating seeds which were artificial inoculating with either non-plant-pathogenic bacteria *Bacillus atrophaeus* and *Escherichia coli* as a model or with actual pathogenic bacteria, e.g. *Xanthomonas*, *Burkholderia plantarii* and *Geobacillus stearothermophilus* often resulted in an efficient reduction of viable bacteria from 2.4 to 6 log units, but simultaneously reduced seed germination in one case [189]. For two studied no information on seed germination after plasma treatment was presented for the same study [42, 242]. Altogether, vegetative cells of *Bacillus atrophaeus* and *Escherichia coli* seemed to be easier to inactivate than spores of *Bacillus atrophaeus* [189]. Disease severity was monitored in one study using

Table 6.2 Efficiency of non-thermal plasma treatment for inactivation of bacterial pathogens in pre-harvest

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Bacterial suspension spotted onto aluminium plates	*Xanthomonas campestris pv. campestris* (Xcc)	Roller conveyer plasma device, atmospheric pressure dielectric barrier discharge (APDBP)	Air, 1.8 to 30 min	Inactivation from 1.5 log units after 2 min to complete inactivation from 3.7 min onwards	[344]
Bacterial suspensions in distilled water	*Erwinia amylovora, Clavibacter michiganensis* subsp. *michiganensis*	Gliding arc discharge plasma	Air 12 min	Lag phase during growth expanded, maximum growth delayed	[230]
Bacterial suspensions in 0.85% NaCl	*Clavibacter michiganensis* subsp. *sepedonicus*, *Dickeya solani*, *Xanthomonas campestris* pv., *Pectobacterium atrosepticum* (Pba), *Pectobacterium carotovorum* subsp. *carotovorum* (Pcc)	Flow through atmospheric pressure glowdischarge (dc-APGD)	Air, 1 min	Cms, Dsol, and Xcc complete inactivation, Pcc and Pba maximum 3.7 log units	[227]
Bacterial suspensions in sterile LB broth	*Erwinia carotovora carotovora, Erwinia carotovora atroseptica, Erwinia chrysanthemi*	Gliding arc discharge	Mixture of nitrogen and oxygen, 1 to 12 min	Lag phase with complete survival up to 4/5 min, rapid decrease in survival up to 7 min, complete inactivation after 8 min	[224]
Bacterial suspensions in sterile LB broth	*Erwinia carotovora*	Gliding arc discharge	Mixture of nitrogen and oxygen, 1–10 min	Rapid loss of survival up to 90% of the initial bacterial population within 2.5 min, second step with slower kinetics, leading to a complete loss survival within 5 min	[223]

(continued)

Table 6.2 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.)	Natural bacterial load, Barley: artificially inoculated with *Escherichia coli*, *Bacillus atrophaeus* (vegetative cells and endospores)	Atmospheric pressure dielectric barrier discharge DBD	Air, 5, 20 min direct and indirect treatment	Barley 20 min treatment time: Natural load reduction by 2.4 and 1.7 log units for direct and indirect treatment, *B. atrophaeus* spores reduction by 2.4 and 1.3 log units for direct and indirect treatment respectively *B. atrophaeus* vegetative cells reduction by 3.2 and 2.7 log units for direct and indirect treatment, respectively *E.coli:* 3.5 and 3.3 log units for direct and indirect treatment Seed germination: strong delay for 20 min direct treatment: Wheat: reduction of natural load by 1.5 and 1.2 log units at 20 min direct and indirect treatment Seed germination: strong delay for 20 min direct treatment	[189]
Seeds of chickpea (*Cicer arietinum*)	Natural bacterial load	Surface microdischarge plasma FlatPlaSter 2.0	Air, 30–300 s	1 log unit reduction till 3 min treatment time, 2 log units reduction from 3–5 min Seed germination reduced by 10–60% for 2–5 min treatment	[216]
Seeds of chinese cabbage (*Brassica campestris* var *amplexicaulis*)	*Xanthomonas campestris*	Low-pressure plasma	Argon 0.5–1.0 L/min, 5–40 min	Reduction of 3–6 log units, no seed germination determined	[242]
Seeds of ginseng (*Panax ginseng*)	Natural bacterial load	Atmospheric pressure dielectric barrier discharge DBD	Argon and argon/oxygen mixture (80:20); 10 min each day, 3 days in a row	Identification using next generation sequencing *Kocuria*, *Variovorax*, *Pseudomonas*, *Duganella*, *Rahnella, Flavobacterium, Azospirillum, Chryseobacterium* Reduction <20% *Pseudomonas Duganella* Reduction 30–65% for all other No decrease in seed germination	[174]
Seeds of maize (*Zea mays* L.)	Natural bacterial load	Diffuse Coplanar surface barrier discharge AP DCSBD CP	Air; 60–300 s	Complete reduction of bacteria from 60 s treatment onwards Decrease in seed germination from 180 s onwards	[380]

(continued)

Table 6.2 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of rapeseed (*Brasica napus L.*)	Natural bacterial load	Corona discharge plasma jet	Air, 1, 2, 3 min	Identification using general and selective growth media *B. cereus, E. coli, Salmonella* spp. Reduction of total aerobic bacteria by 2.2 log units after 3 min treatment Decrease in seed germination by ~30% at 3 min treatment time	[270]
Seeds of rice (*Oryza sativa* 'Haenuki')	*Burkholderia plantarii*	Atmospheric pressure plasma jet	Air, 10 min	Disease severity decreased by 40%, no reduction in seed germination	[246]
Seeds of sweet basil (*Ocimum basili-cum L.*)	Natural bacterial load	Atmospheric pressure surface dielectric barrier discharge SDBD	Humid air; 10–600 s	Decrease in contaminated seeds by maximum 30% at 300 s treatment time No decrease in seed germination	[7]
Seeds of wheat (*Triticum aestivum* L.)	*Geobacillus stearothermophilus*	Atmospheric pressure dielectric barrier discharge DBD	Argon (2.8 nlm), 1–60 min	Up to 15 min reduction by 1 log unit, 3 log units after 60 min No information on seed germination	[42]
Tomato (Solanum lycopersicum L., Rinka 409) seedlings, inoculated via hydroponic nutrient solution	*Ralstonia solanacearum*	Gas-liquid phase discharge plasma reactor	Air, 100 min	Inactivation of pathogen in liquid solution by 5 log units Disease severity of tomato seedlings decreased by 80% after 10 days of growth	[247]
Tomato seeds treated with CAP	*Ralstonia solanacearum* suspension poured onto the soil near the roots of the tomato seedlings at 30 days of growth	Capacitively coupled plasma (CCP) was generated by radiofrequency discharge, 150 Pa	Helium	Increased tomato resistance to *R. solanacearum* with an efficacy of 25%	[140]

artificially inoculated *Burkholderia plantarii* on seeds of rice which were subjected to atmospheric pressure plasma jet, subsequently [246]. Results indicated a reduction in disease severity of seedling blight by 40% along with no reduction in seed germination.

Six studies presented information on the effect of CAP on natural bacterial load on seeds, which of course also encompasses non-pathogenic bacteria. The natural community was identified in two of the six studies [174, 270]. A very recent study by Lee and colleges [174] applied next generation sequencing to elucidate the community on seeds of ginseng identifying the genus *Kocuria*, *Variovorax*, *Pseudomonas*, *Duganella*, *Rahnella, Flavobacterium, Azospirillum* and *Chryseobacterium.* CAP treatment for thre times 10 min using a DBD releveled a reduction by less than 20% for *Pseudomonas* and *Duganella*, as well as a reduction by 30–65% for all other, while a t the same time no negative effects on seed germination were detected. Puligundla and colleges [270] actually focuses on post-harvest relevant bacteria and therefore used general and selective growth media to quantify *B. cereus, E. coli, Salmonella* spp. on rapeseed. For all detected microorganisms the reduction after treatment with a corona discharge plasma jet for 3 min. was in the range of 1.2–2.2 log CFU/g. However, 3 min CAP treatment also provoked a decrease in seed germination by ~30%. The four remaining studies dealt with an unknown community of natural bacterial load on seed surfaces of sweet basil, barley and wheat as well as chickpea and maize showing inactivation by 1.2–3 log units, up to complete inactivation [380] or a reduction by 30% in contaminated seeds [7, 189, 216]. In two of the latter studies, seed germination was severely negatively affected with a decrease by up to 60% [189, 216].

Altogether, seed decontamination/ inactivation often was accompanied by a reduction in seed germination when applying identical CAP treatment times, impeding a possible application of CAP in pre-harvest seed treatment. It has to kept in mind, that plasma can induce a sub-lethal state of bacteria leaving them viable but nonculturable after CAP treatment (VBNC) state [367]. Further investigations on this effect are needed. Previous studies investigating the effect of CAP treatment on bacteria as well as fungi on seed surfaces demonstrated that bacteria especially in vegetative state are more prone to CAP exposure compared to fungi[174, 189, 270, 380].

Some authors investigated and proposed inactivation mechanisms, which resemble some of those found for fungal inactivation. Previous knowledge originating form plasma medicine and/or food science can be transferred regarding some general patterns and concepts for inactivation. Different effects of CAP treatment were observed for Gram-positive and Gram-negative bacteria [147, 167, 198] that differ in cell envelope structures. Gram-negative bacteria, which possess a cell wall composed of an outer membrane and thin peptidoglycan (murein), displayed substantial damage to the membrane resulting in the cytoplasm leakage. Gram-positive bacteria on the other hand, display cells with a thick cell wall and did not show the significant morphological modifications and decontamination was most probably appeared here due to interactions of reactive compounds with the intracellular components [147, 238]. Bacteria morphometry might also be responsible for differences in inactivation patterns with more resistant spherical cells (cocci) than

rod-shaped cells (bacilli) [167, 331]. As pointed out before, CAP produces many reactive oxygen and nitrogen species (RONS), which can oxidize proteins, lipids, and nucleic acids and lead to pathogen destruction [180]. Moreover, inactivation mechanisms might include erosion the surface of microbial cells through etching [218], oxidative damage of intracellular macromolecules, such as membrane lipids, proteins, and DNA, and a reduction in intracellular pH from diffusion into the microbial cells disrupting pH homeostasis [166]. Furthermore, sub-lethal damages can induce viable but non-culturable (VBNC) states in fungi as well as bacteria which is defined as an inactive form of life that is induced by stressful conditions [51] and undergoes recovery under suitable conditions [277]. These state transitions have been reported after CAP treatment [53, 72, 197, 298] and need to be taken into account in future studies.

6.2.4 Effect of Plasma Treatment on Viruses

Plant virology is a very dynamic research area with new plant viruses being detected more rapidly. Moreover, awareness of their pathological impact and severity of economic loss caused by reduction in yield by up to 100% [222, 312] or quality of crops has led to efforts for new detection as well as plant treatment methods. Plant pathogenic viruses are mainly transmitted horizontally by biological vectors, usually insects, but can also be transmitted via seeds, tubers, rhizomes and bulbs [294]. Increasing evidence suggest that transmission can also occur via contaminated process water [205].

The majority of studies dealing with the effect of CAP on plant viruses applied DBDs in various configurations, next to jets and torches for direct treatment and indirect underwater treatment (Table 6.3) of viruses in suspension and inoculated onto plant leaves. Only one study dealt with actual seeds, cucumber and pepper, which were naturally infected with cucumber mosaic virus, zucchini yellow mosaic virus and watermelon mosaic virus [325]. Štěpánová and collegues used only one treatment time per plant species (20 s for cucmber and 4 s for pepper) and detected no decrease in viral load after treatment of seeds with a diffuse coplanar surface barrier discharge plasma (DCSBD). Seed germination on the other hand, was not decreased after plasma treatment. Milusheva and colleagues [212] investigated the effect of a surface-wave-sustained argon plasma torch and an underwater diaphragm discharge on plum tree microplants, which were naturally co-infected by M and D strains of Plum pox virus (PPV). Microplant's nodal segments or leaflets were subjected directly to a CAP torch, as well as to electrical discharges in water media. Treating nodal segments without leaves in gas medium using the torch tip tuned out to be most effective with no detection of viable D strains of Plum pox virus along with a decrease in symptomatic plants by 80%. Plant leaves inoculated with specific viruses were the focus of two studies using Tulane virus for Romain lettuce and tobacco mosaic virus for tobacco [104, 213]. Reduction of Tulane viral load by 1.3 ± 0.2 log PFU/g Romanian lettuce and no necrotic lesions cause by tobacco

Table 6.3 Efficiency of non-thermal plasma treatment for inactivation of viral pathogens in pre-harvest

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Bacteriophage suspensions	T4, Φ174 and MS2 viral strains	Air surface micro-discharge (SMD)	Argon and artificial air (79% nitrogen plus 21% oxygen) to generate plasma-activated water = 10 to 100 s	inactivation below detection limit after 120 s of treatment Aggregation of bacteriophages and damage to nucleic acid and proteins	[101]
Irrigation water	Potato virus Y	Single electrode cold atmospheric plasma jet	Argon (~99%) and oxygen (~1%), 5, 15, 30, 45, 60 min	RNA degradation in the virus material induced complete viral inactivation One infection out of two for 5 min treatment time in plant infectivity assay using *Nicotiana tabacum,* cv. 'White Burley', no infection from 5 min onwards	[86]
Leaves of Romain lettuce (*Lactuca sativa* L. var. *longifolia*) Post-harvest	Tulane virus	Atmospheric pressure dielectric barrier discharge DBD	Air inside the package, 5 min	Reduction of viral load by 1.3 ± 0.2 log PFU/g lettuce	[213]
Plum tree (*Prunus domestica* L., cv 'Kyustendilska sinya') microplants	naturally co-infected by M and D strains of Plum pox virus (PPV)	Surface-wave-sustained argon plasma torch and an underwater diaphragm discharge	Argon 2 l/min, 5 s	PCR and visual analysis, D strains of Plum pox virus (PPV) inactivated, only M strain detectable with PCR Decrease in number of symptomatic plants by 80%	[212]

(continued)

Table 6.3 (continued)

Target	Pathogen	Plasma type and source	Gas type and exposure time	Effect	References
Seeds of cucumber (*Cucumis sativus* L.) and pepper (*Capsicum annuum* L.)	Naturally infected CMV Cucumber mosaic virus ZYMV Zucchini yellow mosaic virus WMV Watermelon mosaic virus	Diffuse Coplanar Surface Barrier Discharge (DCSBD)	Air, cucumber 20 s Pepper 4 s	No reduction in CMV, ZYMV, and WMV diseases No reduction in seed germination	[325]
Tobacco (*Nicotiana*) leaves	Inoculated with Tobacco mosaic virus solution	Atmospheric pressure dielectric barrier discharge DBD	Air, 0.5–10 min	No necrotic lesions on TMV irradiated leaves for 5 and 10 min irradiation	[104]

mosaic virus detectable in plant leaves after treatment. Filipić and colleges [86] investigated irrigation water inoculated with Potato virus Y wich was treated using a single electrode cold atmospheric plasma jet. No infection was detected in the plant infectivity assay using *Nicotiana tabacum* cv. 'White Burley' from 15 min treatment time of suspension onwards.

Possible mechanisms for viral inactivation were presented in a study by Guo and colleges [100], who did not investigate plant viruses but bacteriophages T4, Φ174 and MS2, which can serve as a general proof of concept for inactivation. Bacteriophage suspension was treated with PTW produced by an air surface microdischarge, showing an inactivation below the detection limit after 120 s treatment. Although not being pathogenic to plants, the proposed model of inactivation is likely to be adaptable from bacteriophages. The proposed model of inactivation includes plasma-generated reactive species, especially singlet oxygen, which efficiently inactivated different kinds of bacteriophages in water, including double-stranded DNA, single-stranded DNA, and RNA bacteriophages by damaging both nucleic acid and proteins and leading to excessive aggregation of the bacteriophages. In addition, knowledge can be transferred form studies dealing with other types of viruses, e.g., animal viruses. Work on Newcastle disease (ND), an infectious viral disease of avian species, reported complete inactivation after PTW treatment resulting most likely from singlet oxygen, which quickly reacts with cysteine, resulting in the formation of cystine (R-cys-S-S-cys-R) with disulfides; thus creating products which lead to aggregation of bacteriophages [362]. Furthermore, enzyme activity can be impaired by hydroperoxides which is formed by the interaction of amino acids, including tyrosine, tryptophan, and histidine, which selectively interact with singlet oxygen [63].

Altogether, studies dealing with the efficiency of CAP to inactivate plant pathogenic viruses on seeds and plants are scarce and efforts should be taken to fill the gaps of knowledge. Unknown up to now is the effect of CAP itself on insects as transmission vectors, which should be examined in the future. In addition, in natural environments mixed-infections with two or more plant viruses are frequent, with viruses being able to interact in multiple and intricate ways. These interactions can be synergistic, antagonistic, or neutral and will likely have an impact on the efficiency of CAP application for phytosanitary purposes.

6.3 Application of Non-thermal Atmospheric Pressure Plasma to Seed Germination and Plant Growth

Major seed dressing methods are aiming to prevent pathogenic attack and outbreak by using e.g. fungicides. Inoculation of seeds with fertilizers, chemical stimulants or plant growth promoting bacteria (PGPB) support seed germination performance to promote proper seedling establishment, further plant growth and stress resilience to

finally secure or increase yield. Furthermore, different kinds of chemical and physical seed treatment methods have been studied aiming to stimulate and synchronize germination of seed population and to prime plants against various stresses [9, 78, 251]. Numerous studies have shown that plasma as a physical treatment method can improve seed germination performance and plant growth (Tables 6.4 and 6.5). Recent studies investigated the potential of plasma to prime seeds against biotic and abiotic stressors as well [14, 17, 80, 84, 99, 178, 219, 264].

Unlike in plasma medicine, there is a much greater variability of plasma sources and a higher number of plant species to be treated. In contrast to human or animal tissue surfaces, the surface of seeds consists of dead cellular material and water-repellent polymer layers to protect the plant embryo from physical and chemical influences [26]. Another difference is that, in contrast to animal organs, the entire seed is treated, not single specific parts of it. In addition, seeds are not treated as a single individual, but usually in a batch with a large number of seeds at the same time. Therefore, there is a need to develop devices for treatments on a larger scale, which will be necessary for future agricultural application. Thus, the requirements for plasma source dimensions to treat plant seeds along with a greater flexibility of plasma processes and operation conditions need to be addressed. Section 6.3 focuses on gaseous plasma treatment of seeds under atmospheric and low-pressure conditions comprising the plasma effects on physicochemical alterations of the seed and on germination and developmental processes.

A wide range of options exists to generate non-thermal plasma. This refers to configuration of electrodes, applied pressure, feed gas composition and flow rates, and electrical parameters (voltage, type of electrical current, frequency, power) used to ignite plasma, as well as treatment times and the mode of treatment with respect to direct or indirect plasma exposure of the plant target, as can be seen in Tables 6.4 and 6.5. In general, dielectric barrier discharges (DBD) in different configurations such as surface DBD (planar DBD) or diffuse coaxial DBD (DCSBD), gliding arc discharges, jets, corona discharges, microwave discharges as well as different kinds of radio-frequency (RF) discharges exist and has been applied. For treatment of seeds under atmospheric pressure, dielectric discharges using AC, DC or even RF were most frequently studied so far (Table 6.4). Regarding low-pressure conditions, RF plasmas were mostly investigated (Table 6.5).

Proper seed germination and seedling establishment on the field is the fundamental requirement for resilient plant growth, which ultimately determines the yield. Here, plasma has relevance for potential future application in agriculture as many studies have proven the beneficial effects of non-thermal plasma on seed germination performance. Important agricultural relevant plant species with different usages ranging from food and feed production to pharmaceutical and plant-based industry have been investigated so far (Tables 6.4 and 6.5). Wheat (e.g. [38, 99, 207]), maize (e.g. [381]), rice (e.g. [150, 373]) and barley (e.g. [38, 267]) produce seed-like fruits (botanical term “caryopsis”; caryopses are propagation units and the term “seeds” will be used within this chapter for simplification) containing a starchy endosperm important for feed and food production. Legume seeds such as soybean (e.g. [175]), pea (e.g. [151, 330]), chickpea (e.g. [216]), common and mung bean (e.g. [35, 281,

Table 6.4 Effects of atmospheric pressure plasma on plant seeds

Plant species	Plasma parameters	Observed effects	References
Family: Violaceae papaconha *Hybanthus calceolaria* (L.) Schulze-Menz	DBD driven plasma jet at 8.1 kV and 720 Hz FG: He GF: 2 L min^{-1} TT: 1, 5, 10 min	• Enhanced seed germination speed and max. germination for 1 min plasma TT • Decreased WCA • Elevated imbibition by ~30% for all plasma TTs • No change in electrical conductivity	[60]
Family: Cucurbitaceae cucumber *Cucumis sativus* L. var. Regina F1 and Family: Solanaceae pepper *Capsicum annuum* L. var	DCSBD at AC with 15 kHz and 20 kV peak-to-peak FG: air Power density: 100 W cm^{-3} TT: 10–50 s (cucumber), 4–15 s (pepper)	• SEM pictures showed no evidence of structural damage for shorter TTs (cucumber: 12 s, pepper: 4 s) • XPS revealed a relative increase in oxygen containing groups which were still observable for plasma-treated seeds (cucumber: 12 s, pepper: 4 s) after seed storage of 9 days • Germination percentage monitored at two observation times was increased for both plant species at TTs of 10–40 s for cucumber and at TTs >12 s for pepper	[325]
Family: Acanthaceae green chiretta *Andrographis paniculata* (Burm.f.) Nees	Planar DBD at different voltages 3.4, 4.25, 5.1, and 5.95 kV FG: air TT: 10 and 20 s	• SEM analysis revealed erosion of seed surface that were more pronounced for seeds treated with plasma at 5.95 kV for 10 s • Permeability of seeds was significantly accelerated for seeds treated with 5.95 kV at 10 s TT and significantly decreased for seeds treated with 3.4 kV at 20 s TT • Positive trends on seed germination parameters and seedling emergence could be observed which were not consistently significant upon plasma treatment parameters • SOD activity and MDA content in seedling leaves was lower for almost all applied plasma treatment parameters of seeds, while CAT activity and tended to increase	[343]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Alliaceae onion *Allium cepa* L. cv. Wolska	Plasma jet at RF and 1 kV FG: He/O_2, He/air ratio of 3:2 GF: 710 L h^{-1} Power: 45 W TT: 2, 5, 10, 15 s	• SEM analysis revealed no changes in surface structure • Significant increase in germination speed for He/O_2 (TT $\leq$ 10 s) and for He/air (TT $\geq$ 10 s) • Significant increase in max. germination for 10 s plasma-treated seeds with both gas mixtures • Seedling lengths of He/O_2 and He/air plasma-treated seeds were unchanged during the first 7 days of growth, but were significantly increased during further growth for 5 days	[340]
Family: Amaranthaceae spinach *Spinacia oleracea* L.	High voltage nanosecond pulsed plasma at 6 kV and 0.7 kA FG: air Discharge energy: 0.3 J per one shot pulse, TT: 1, 5, 10 shots	• SEM analysis revealed morphological alterations of seed surfaces • Germination and dry weight of seedlings increased after high voltage short pulse shots (1 and 5 shots) • Longer TT (10 shots) had negative effects on seed germination rate and seedling growth • Levels of GA3 hormone and pullulanase mRNA was elevated in 1 day germinated seeds except for 10 shots treated seeds	[136]
Family: Amaranthaceae spinach *Spinacia oleracea* L.	Micro DBD at 6 kV, 14 mA and 22 kHzFG: air, N_2 GF: 1.5 L min^{-1} TT: 0.5, 1, 3, 5 min	• SEM analysis revealed no alteration of seed surfaces • Air DBD plasma exhibited slightly higher germination and seedling growth than those treated with N_2 plasma • Levels of pullulanase mRNA was unchanged in one day germinated seeds • Increased chlorophyll content in 5-weeks old spinach seedlings from air DBD plasma-treated seeds with TTs $\leq$ 3 min • Increase in total polyphenol content in 5-weeks old spinach seedlings from N_2 DBD plasma-treated seeds with TTs $\geq$ 3 min	[136]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Amaranthaceae spinach *Spinacia oleracea* L.	High voltage nanosecond pulsed plasma at 6 kV and 0.7 kA FG: air Discharge energy: 0.3 J per one shot pulse TT: 1, 5, 10 shots	• WCA was significantly decreased after 1 shot plasma treatment, while WU was unaffected • Raman and FTIR spectroscopy analyses revealed no chemical modification of the seed coat • Germination percentage of 7-days germinated seeds was significantly higher for 1 and 5 shots plasma treatment, while germination of 10 shots plasma-treated seeds was unchanged • GA hormone level and starch hydrolysis (hydrolytic activity and pullulanase transcript level) was significantly elevated within 24 h in germinating seeds plasma-treated by 1 shot	[138]
Family: Apiaceae cumin *Cuminum cyminum* L.	DBD at 10 kVand 15 kHz FG: Ar GF: 9 L min^{-1} TT: 5 and 10 min	• SEM analysis of seed surfaces revealed damaging effects of plasma for both plasma TTs • WU was significantly accelerated for both plasma TTs • Germination percentage at day 7 of germination time was significantly higher for both plasma TTs • Biomass (dry weight, shoot and root lengths, root area and volume) and biochemical (chlorophyll and carotenoid content) parameters of 4 weeks old seedlings were significantly increased for 5 min plasma-treated seeds while 10 min TT led to reduced seedling growth • Leaves of seedlings from 5 min plasma -treated seeds had higher contents of N, P, K, Mg, Ca and Fe elements • Significant higher ROS levels in leaves were detected for both TTs and more pronounced for 10 min plasma-treated seeds • Proline content in seedling leaves was markedly increased for 5 min plasma-treated seeds while MDA content was strongly increased in seedling leaves of 10 min plasma-treated seeds • SOD, CAT, APX and GR activities were significantly increased in seedling leaves of 10 min plasma-treated seeds, while 5 min plasma treatment resulted significant decrease in APX and GR activity while SOD and CAT activities were unchanged	[280]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Apiaceae coriander *Coriandrum sativum* L.	Micro DBD at 15.4 kHz and ~0.6 kV FG: Ar, N_2, air GF: 1 L min^{-1} Energy: 0.94 (Ar), 0.92 (air), 1.04 (N_2) J s^{-1} TT: 30, 60, 180 s (4-times each with 24 h interval)	• SEM analysis revealed structural degeneration of the seed surface with increasing TT of N_2 plasma • Significant positive effects on germination performance was observed for N_2 plasma at TTs ≤ 60 s, while germination of plasma-treated seeds at 180 s was unchanged • Positive trends on seed germination for air plasma-treated seeds were overlapped by high standard deviations • Mean values of germination percentage of 60 and 180 s Ar plasma-treated seeds were lower but without significance • Polyphenol content was elevated in 2 weeks old seedlings from 60 s N_2 plasma-treated seeds and dropped down after 4 weeks of growth, while elevated polyphenol content of seedlings from 180 s N_2 plasma-treated seeds were recorded in 4 weeks old seedlings only	[135]
Family: Apiaceae coriander *Coriandrum sativum* L.	Microwave plasma torch at 2.45 GHz FG: N_2/O_2 mixture GF: 10 L min^{-1} for N_2 with 50, 100, 200, 300 sccm for O_2 Power: 400 W TT: 5 and 10 min	• Germination percentage at day 5, max. germination and lengths of 3 weeks old seedlings were significantly increased for plasma treatment parameters at O_2-GF ≥ 200 sccm and both TTs • The observed positive effects were attributed to the increasing occurrence of NO with increasing O_2 flow rate in the N_2/O_2 gas mixture	[135]
Family: Araliaceae dehisced ginseng *Panax ginseng* C.A.Mey	Planar DBD at ~8,4 kV and 60 Hz FG: Ar, Ar/O_2 (80%/20%) GF: 1 L min^{-1} TT: 10 min (3 times with 24 h interval)	• Germination was significantly elevated for Ar/O_2 plasma-treated seeds during 10-days oberservation time, while for Ar plasma-treated seeds increased values for germination percentage were only observed after 7 days of germination • Ar/O_2 plasma treatment of seeds resulted in increased root lengths of 10 days old seedlings, while seedlings of Ar plasma-treated were unaltered	[174]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Asteraceae sunflower *Helianthus annuus* L. var. Nyķrségi fekete	DBD at 7 kV and 14.4 kHz FG: air Power density: 3.05 W cm^{-2} TT: 5, 7, 9, 11 min	• Dry seeds displayed changes in phytohormone levels (ABA, gibberellin, auxin, cytokinins, salicylic acid) after 7 or 11 min plasma treatment • Content of ABA was significantly decreased for both TTs, but gibberellin species GA7 was significantly increased in 7 min plasma-treated seeds while gibberellin species GA3 and GA7 were significantly decreased in 11 min plasma-treated seeds • No significant positive effects on germination parameters (max. germination, median germination time, uniformity) could be observed under laboratory germination conditions • Germination in substrate of 7 and 11 min plasma-treated seeds resulted in negative effects on germination kinetics but max. germination was not affected • Biomass parameters (weight and length) of 9 day old seedlings were not changed, except that 11 min plasma-treated seeds had significantly reduced seedling length • Biomass parameters (plant and leaf weight, root length) and photosynthetic performance of 30 days old plants grown in substrate from 7 min plasma-treated seeds were significantly increased while these parameters were significantly decreased for 11 min plasma-treated seeds	[390]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Asteraceae sunflower *Helianthus annuus* L.	Pin-shaped multi-corona discharge plasma at 8, 10, 12 and 14 kV FG: Ar/O_2 mixture GF: Ar: O_2 flow rates of 4: 2, 3: 3, 2: 4 L min^{-1} TT: 1, 3, 5 min	• Most of the applied plasma parameter combinations with different GF ratios, voltages and TTs, resulted in positive effects on seedling growth (dry weight and shoot lengths) • Positive effects on seedling shoot growth at 5, 6 and 7 days of cultivation time observed for all applied plasma parameters (Ar/O_2 mixture with 3 L min^{-1} each at 8. 10, 12 and 14 kV for 1 min), • Plasma treatment (Ar/O_2 mixture with 3 L min^{-1} each, at 8 kV) of seeds for 1, 3 and 5 min resulted in higher shoot lengths of 7 days old seedlings • All applied voltages and TTs for Ar/O_2 mixtures with 3 L min^{-1} each led to higher values for dry weight and shoot lengths of 7 days old seedlings	[203]
Family: Asteraceae sunflower *Helianthus annuus* L.	Planar DBD FG: air Power: 90 W TT: 30, 60, 90, 120 s	• WCA significantly decreased with increasing TT • WU values did not correlate with TT • Slightly increased WU values for 60 and 120 s TTs and slightly decreased WU values for 30 and 90 s TTs were observed • Germination percentage at day 5 of germination time was higher for all plasma TTs • Seedling lengths were slightly increased for TTs > 60 s, while 30 s plasma treatment resulted in slightly lower values during seedling growth for 7 days • Seedling fresh and dry weights were slightly higher for 60 and 90 s plasma-treated seeds	[371]
Family: Brassicaceae broccoli *Brassica oleracea* L. var. kialica plen	Corona discharge plasma jet at 20 kV and 58 kHz FG: air TT: 1, 2, 3 min	• Elevated germination after 1 min plasma TT and strongly impaired germination after 3 min plasma treatment • Seedling weight and length was elevated for 1 and 2 min TTs, but decreased at 3 min TT • No change in reducing sugars content, total phenolic content and radical scavenging activity was observed	[157]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Brassicaceae broccoli *Brassica oleracea* L.	Multi plasma jet at 76 kHz FG: Ar GF: 4.2 lpm Power: 412 W TT: 20 – 80 s	• SEM analysis revealed slight smoothening of seed surface which was most pronounced in seeds treated with plasma for 80 s • WCA decreased strongly with the increase in TT • Germination tests and seedling growth with 30 and 60 s plasma-treated seeds revealed higher max. germination but no change in germination rate for both TTs • Shoot lengths of 7 days old seedlings were unchanged but shoot weight was slightly increased for 30 s treated seeds and decreased for 60 s plasma-treated seeds	[321]
Family: Brassicaceae radish *Raphanus sativus* L.	DBD at 7 kV and 14.4 kHz FG: air Power density: 3.05 Wcm^{-2} TT: 1, 3, 5, 7, 9, 15 min	• All applied plasma TTs resulted in significant positive effects on seed germination parameters (max. germination, median germination time) when freshly harvested dormant seeds were treated with plasma • Effects on germination correlated with decreased ABA and increased GA levels in seeds, auxin levels were unchanged but cytokinin levels were significantly elevated, too • Plasma treatment for 5 min of less dormant seeds (5 month storage) did not lead to improved germination parameters but decreased ABA and increased GA levels were observed as well	[67]
Family: Brassicaceae radish *Raphanus sativus* L. var. caudutrus	Multicorona air Plasma at 30 kV and 13.5 kHz FG: air TT: 2 and 4 min	• Slight acceleration of germination was observed for 2 min plasma-treated seeds with increased dry weight in 7 days old seedlings • Significantly increased shoot length without change in dry weight in 7 days old seedlings from 4 min plasma-treated seeds • Moisture content was elevated in 7 days old seedlings for both TTs	[337]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Brassicaceae thale cress *Arabidopsis thaliana* (L.) Heynh ecotype Columbia	DBD at 10 kV and 9.7 kHz FG: air TT: 15 min plasma jet FG: He GF: 3 L min^{-1} TT: 15 min	• SEM analysis of air DBD plasma treated seeds revealed strong roughening of seed surface • Germination defined as testa rupture was significantly elevated after He jet and air DBD plasma-treatment and the effect was stable during observation time of 40 h, as monitored for air plasma-treated seeds • Decrease in seed coat permeability (tetrazolium test) of air DBD plasma-treated was observed	[16]
Family: Brassicaceae thale cress *Arabidopsis thaliana* (L.) Heynh	DBD at 10 kV and 10 kHz FG: air TT: 15 min	• Germination of wild type seeds was elevated under saline conditions up to 65 h of germination time • Germination of mucilage-deficient mutant seeds was significantly accelerated und under normal and saline germination conditions, while germination of cuticle-deficient mutant seeds was strongly impaired after plasma treatment under both germination conditions • No change in max. germination was observed for all seed types and germination conditions • A decrease in seed permeability (tetrazolium red) after plasma treatment was observed for all seed types • Hydrophobic compounds on seed surface were changed for all seed types	[17]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Brassicaceae thale cress *Arabidopsis thaliana* (L.) Heynh and Family: Brassicaceae camelina *Camelina sativa* (L.) Crantz	DBD at 10 kV and 10 kHz FG: air TT: 1 and 15 min	• SEM analysis revealed strong roughening of seed surface with increasing TTs for both plant species • WCA was strongly decreased with increasing TTs for both plant species • WU was slightly improved for both plant species, while permeability of seeds was strongly decreased • Lipid analysis of Arabidopsis plasma-treated seeds revealed a decrease in saturated and an increase in unsaturated fatty acids, while in camelina both fatty acid types were reduced • Arabidopsis germination rate was almost unchanged while max. germination was increased especially for 15 min TT • Camelina germination rate and max. germination was positively affected after 1 min, while 15 min plasma treatment had negative effects on germination • The area of camelina cotyledons of 1 min treated seeds were significantly increased while the cotyledons of 15 min plasma-treated seeds had similar size as controls at day 5 of germination	[18]
Family: Brassicaceae thale cress *Arabidopsis thaliana* (L.) Heynh	DBD at 8.47 kV and 7.95 kHz FG: air Power: 2.5 W TT: 0.5, 1, 3, 5, 10 min	• SEM-EDX analysis revealed a plasma dose-dependent etching effect on the seed surface with increased surface oxidation • Short plasma TTs $\leq$ 3 min led to improved seed germination and seedling growth (fresh weight, root length), while plasma TTs < 5 min had inhibitory effects • MDA, ROS and RNS levels in seeds directly after plasma treatment were enhanced • H_2O_2 levels in 7 days old seedlings were higher for $\geq$3 min plasma-treated seeds • CAT, SOD, and POD activities as well as proline level in short-time plasma-treated seedlings were apparently higher	[54]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Brassicaceae thale cress *Arabidopsis thaliana* (L.) Heynh	Planar DBD FG: air Power: 2.17 W Power density: 1.49 W cm^{-2} TT: 3 min	• Plasma treatment led to earlier maturity (2,5 days earlier), earlier harvest day (6 days earlier), elevated total seed weight of harvest and elevated number of seeds produced	[160]
Family: Brassicaceae thale cress *Arabidopsis thaliana* (L.) Heynh and Family: Asteraceae zinnia *Zinnia Peruviana* L.	DBD FG: air Power density: 1.49 W cm^{-2} TT: 3 min	*Arabidopsis* • Long term effect: in the third generation, the leaf area is 2 times larger than that without plasma irradiation and the stem length is 1.5 times longer than that without plasma *Zinnia* • In the second generation, the stem length is 2 times longer than that without plasma	[292]
Family: Brassicaceae thale cress *Arabidopsis thaliana* (L.) Heynh	Plasma (not specified) at 7.2 kHz FG: air Power density: 0.042 W cm^{-2} TT: 0.5, 1, 2, 3, 4, 5 min	• Plasma treatment for 1 min significantly promoted seedling growth • ABA level in seedlings increased and peaked 48 h after treatment, but were lower than in the control after 96 h • Transcript levels of ABA signalling genes markedly enhanced at 48 h, but significantly downregulated after 96 h • Plasma treatment reduced stomatal aperture after 24 h, accelerated ROS accumulation in guard cells • Ca^{2+} level in the treatment group higher than in the control at 24 and 96 h	[352]
Family: Brassicaceae radish *Raphanus sativus* L.	Plasma torch FG: O_2/ air GF: 1 slm Power: 5 W TT: 10, 20, 30, 60 min	• Increased germination speed after 24 h • Increased max. germination after 70 h • Elevated sprout length by 5 cm after 95 h of growth for O_2 plasma	[108]
Family: Brassicaceae radish *Raphanus sativus* L.	Surface discharge plasma at 50 Hz, and 15 kV FG: air GF: 1 min^{-1} Power: 2.7 W TT: 20 min	• Little effect on the germination rate, but influenced the early growth of seeds • Sprouts and roots of plasma-treated seeds were longer and heavier than those of control seeds • Best results were obtained for 20 min TT, where an increase of the length of roots and sprouts	[208]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Brassicaceae radish *Raphanus sativus* L.	Corona discharge plasma jet at 20 kV 1.5 A and 58 kHz FG: air GF: 2.5 m s^{-1} TT: 1, 2, 3 min	• The plasma seed treatment for up to 2 min showed beneficial effects on seed germination rate and growth of seedlings • Compared to untreated controls, sprouts grown from plasma-treated seeds no significant changes in the levels of moisture reducing sugars total phenolic content and DPPH radical scavenging activity	[271]
Family: Brassicaceae radish *Raphanus sativus* L.	DBD FG: air Power density: 1.49 W cm^{-2} TT: 3 min	• No information on germination • Seedling length elevated after Plasma treatment • Response of plants to the plasma irradiation becomes gradually weak with time, ratio of plant length with plasma irradiation to control decreases from 3.7 at the first day to 1.3 at 7 day	[291]
Family: Brassicaceae radish *Raphanus sativus* L.	DBD at 9.2 kV and 0.2 A FG: air, O_2, NO, He, Ar, N_2 GF: 6 NL min^{-1} Power density: 1.49 W cm^{-2} TT: 60–180 s	• No information on germination • Enhanced plant growth for O_2, air and NO (10%) + N_2 feeding gases plasma • No significant growth enhancement for He, N_2, and Ar gases plasma • Humid air plasma irradiation was more effective in growth enhancement than dry one, >2.3 times faster growth was observed by 3 min air plasma irradiation	[293]
Family: Brassicaceae rapeseed *Brassica napus* L.	Corona discharge plasma jet at 20 kV, 1.5 A and 58 kHz FG: air GF: 2.5 m s^{-1} at inter-electrode gap TT: 1, 2, 3 min	• Plasma treatment of seeds up to 2 min showed positive effects on their germination rate and seedling growth • Physicochemical and sensory characteristics of rape sprouts unaffected due to plasma treatment of their respective seeds	[270]
Family: Cannabaceae hemp *Cannabis sativa* L.	Gliding arc at 50 Hz FG: air GF: 10 L min^{-1} TT: 180, 300, 600 s	• Differences in response among seeds of three hemp cultivars (‘Finola’, ‘Bialobrzeskie’, ‘Carmagnola’) • Positive/neutral effect was observed in all measured characteristics after gliding arc plasma pre-treatment • Gliding arc pre-treatment increased the length of seedlings, seedling accretion and weight of seedling in both cv. ‘Finola’ and cv. ‘Bialobrzeskie’ hemp	[306]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Cucurbitaceae watermelon *Citrullus lanatus* (Thunb.) Matsum. & Nakai var. Niagara	Atmospheric plasma jet at power supply output 10 kV, 30 mA and 20 kHz FG: N_2 TT: 2, 4, 6, 8, 10 min	• WU was significantly increased with strongest increase at 2 min TT, but no difference to control after 11 h of soaking • Germination after 4 days: significant increase in germination for all TTs, most pronounced at 4 min • Max. germination after 10 day: no difference between control an 2 min, significant increase for all other TTs • Seedling (shoot and root) length after 10 days: elevated for all TTs • Seedling weight: no difference between control and 2 min	[191]
Family: Cucurbitaceae bitter melon *Momordica charantia* L.	DBD FG: Ar GF: 2 L min^{-1} Power density: 0.84 W cm^{-2} TT: 60 and 120 s	• Seed priming with plasma and/or multi-walled carbon nanotubes (MWCNT) led to the dramatic increase in growth-related traits, like root and shoot lengths, fresh and dry mass, vigor index, and leaf length • Simultaneous treatments with MWCNT and plasma amplified their individual effects • Uptake and transportations of MWCNTs from the root to leaves were manifested using an electron microscopy • The ultra-structural study revealed that plasma enhanced MWCNT uptake and accumulation • Modifications in organogenesis and differentiation patterns of tissues, especially vascular system, were provoked by the MWCNT and/or plasma treatments, • Plasma and MWCNT reinforce conducting xylem tissue • Long-term effects of MWCNT and/or plasma treatments on reproductive stage: increase in the number of produced flowers, and the decrease in the time of fructifying, caused by the MWCNT and/or plasma treatments	[299]
Family: Cucurbitaceae pumpkin *Cucurbita pepo* L. cv. Cinderella and *Cucurbita maxima* L. cv. Jarrahdale, cv. Warty Goblin	Plasma jet at 10 and 6 kHz FG: Ar/He GF: 2 L min^{-1} TT: 1 and 25 min	• Plasma jets accelerated the germination of pumpkin seeds • Changes in WCA and hydrophilicity	[349]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae fenugreek *Trigonella foenum-graecum* L.	Plasma jet at 16 kV and 24 kHz FG: Ar GF: 2 slpm TT: (1st) 30 s, 1, 5, 10, 15, 20 min; (2nd) 10 s, 30 s, 1, 5, 10, 15 min	• Enhanced seed germination rate for 30 s and 15 min, no change in max. germination • Increase in shoot fresh weight was observed, especially at 10 min TT, • Root:shoot ratio was lower in plasma-treated seedlings, compared with the control plants • Accelerating grounded (AG) electrode: O-radical emission line (777.4 nm) enhanced 5 times	[77]
Family: Fabaceae chickpea *Cicer arietinum* L.	Surface microdischarge (SMD) FG: air Power density: 10 mW cm^{-2} TT: 0.5–5 min	• Germination speed elevated for 0.5–4 min TT • Max. germination enhanced for 0.5–2 min • Seedling length and dry weight: increased for 0.5–2 min TT	[216]
Family: Fabaceae white leadtree *Leucaena leucocephala* (Lam.) de Wit	DBD at 17.5 kV and 990 Hz with pulsed DC mode FG: air TT: 3, 9, 15 min	• WCA was significantly decreased for all plasma TTs • Germination increase after plasma treatment by 3% (15 min) after 11 days of counting	[5]
Family: Fabaceae mung bean *Vigna radiata* (L.) R. Wilczek	Plasma jet FG: Ar GF: 13 slm Power: 80, 140, 200 W TT:1 min	• Induce significantly more water absorption and lead to a higher speed of germination, max. germination did not differ • WCA decrease after plasma treatment with 200 W only • Seedling morphology changed to short radicle and longer hypocotyls with a larger diameter • GABA in plasma-treated beans was approximately 3 times higher than the untreated group at 80 W treatment	[49]
Family: Fabaceae lentil *Lens culinaris* Medik	Seed-packed dielectric barrier at 6 kV in amplitude at 600 Hz device (SP-DBD) FG: He/N_2 GF: 2 slm/ 150 sccm TT: 20 min	• No impact is evidenced on germination rates • Median germination time decreasing from • Addition of molecular oxygen to the helium discharge does not promote seeds' vigor • Increased water absorption	[74]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae pea *Pisum sativum* L. and Family: Cucurbitaceae zucchini *Cucurbita pepo* L.	FSG plasma device at applied voltage was 15 kV FG: air GF: 5 L min^{-1} TT: 30 and 60 s	Pea: • Max. germination elevated for 30, 60 s • Germination speed slower for 30 s • Seedling length and dry weight increased for 30, 60 s, Zucchini: • Max. germination elevated for 30, 60 s • Germination speed slower for 30 s • Seedling length and dry weight increased for 30, 60 s • Drought resistance and germination of seedlings increased after plasma was applied to seeds at 30 s, while seeds treated whiten	[151]
Family: Fabaceae soybean *Glycine max* (L.) Merr	Planar needle array DBD at 50 Hz FG: O_2 and N_2 GF: 6 slm Power: 65 W or 85 W TT: 1, 2, and 3 min	• No significant effect on seed germination • Reductions in CAT activity and increments in glutathione content after plasma treatment, reversing the oxidative damage caused by pathogenic fungi	[264]
Family: Fabaceae lentil *Lens culinaris* Medik	SCDBD at 9.25 kV, 13.33 kH FG: air Power: 858.5 W TT: 0–10 min	• Seed quality: number of dead seeds increased for TTs > 180 s • Accelerated growth of seedlings for short plasma treatment (<120 s) as seen in percentage of hypocotyl and leaf emergence at 3 days • WCA revealed increased seed wettability	[357]
Family: Fabaceae common bean *Phaseolus vulgaris* L.	Plasma jet at 9 kV, 16 mA, 6 kHz FG: He GF: 2.0 L min^{-1} TT: 12, 25, 40, 45, 50 min	• WCA: decrease at 50 min • Germination: increase with increasing cap exposure time • Seedling length: elevated for 1 and 15 min plasma treatment	[348]
Family: Fabaceae lentil *Lens culinaris* Medik	Stacked volume DBD at 6 kV and 500 Hz FG: He/N_2 GF: 1 slm/150 sccm TT: 2–20 min	• Increased speed in germination • Accelerated for different sequences of stirring or randomizing for repeated treatment cycles instead of one long time period • Decrease in WCA greatest for stirring and repeated treatment	[73]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae mimosa *Mimosa caesalpiniafolia* Benth	DBD at 990 Hz (pulsed) and 35 kV FG: air Power density: 0.18 W cm^{-2} TT: 3, 9, and 15 min	• Wettability (WCA) and imbibition were found to be directly related to the treatment duration, but saturation of the imbibition was found for treatment durations greater than 9 min • Plasma treatment strongly improved germination, especially for short TT	[59]
Family: Fabaceae mulungu *Erythrina velutina* Willd	DBD FG: He GF: 0.03 L s^{-1} Power: 150 W TT: 60 s	• Only slightly better germination performance with 5% higher germination percentage after 25 days • Plasma treatment changed the wettability (WCA) of the hilum more effectively than it changed the micropyle	[6]
Family: Fabaceae pea *Pisum sativum* L. var. Salamanca	Surface DBD at 6 to 12 kV and 3.0 kHz FG: air TT: 1, 2, 3, 5, 10 min	• Significant increase in germination after 24 h for 1, 2, 3 min, after 48 h elevated for 3 and 5 min but not significant • Shoot length of 16-days old seedlings was reduced and only a very minor effects on the dry weight were observed • Seedlings from 5 min plasma-treated seeds had lower max. photochemical efficiency of photosystem II • Plasma treatment had effects on flavonoid glycosides in seedlings	[40]
Family: Fabaceae pea *Pisum sativum* L.	Planar DBD FG: air Power: 9–35 W TT: 1, 3, 5, 7, and 10 min	• Elevated seedling length, chlorophyll a, dry weight, with max. change at 15 W • Increased WU most pronounced for 15 W	[89]
Family: Fabaceae pea *Pisum sativum* L. var. Prophet	DBD at 10 kV, 14 kHz FG: air Power density: 2.3 W cm^{-2} TT: 60–600 s	• Increased in germination percentage and growth parameters root and shoot length • Increased biosynthesis of auxin and cytokinins as well as their catabolites and conjugates • 600 s plasma treatment changed seed surface morphology with abrasion and loosening of testal areas • WU most noticeable increased within the first 2 h but later saturation and comparable to controls	[330]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae pea *Pisum sativum* L. cv. Prophet	DCSBD at 14 kHz sinusoidal high voltage with an amplitude up to 20 kV peak-to-peak FG: air, O_2, N_2 GF: 3 L min^{-1} Power density: 80 W cm^{-3} TT: 60, 180, 300 s	• Significant positive effect of air and N_2 plasma treatment TT of 60 s on germination and growth parameters • Increased levels of radicals in young 3-day old seedlings and activation of antioxidant enzymes	[334]
Family: Fabaceae pea *Pisum sativum* L.	DBD at 14 kHz, 20 kV FG: ambient air, N_2, O_2, mixtures (O_2:N_2 = 20:80; 40:60; 60:40; 80:20) GF: 3 L min^{-1} Power: input 400 W TT: 60, 180, 300 s	• Ambient air plasma appears to be the most advantageous for the plasma treatment due to no significant DNA damage • More DNA damage than in non-treated samples; an ambient air plasma had the least damaging effects on seed DNA, compared to plasma treatment with different mixtures of O_2 and N_2	[342]
Family: Fabaceae soybean *Glycine max* (L.) Merr	Needle to plane DBD at 0–25 kV operating at 50 Hz FG: N_2 and O_2 GF: 6 NL min^{-1} TT: 60 – 180 s	• Plasma treatment increased germination, plant growth (root, shoot length, foliar area, fresh weight), promoted a normal and healthy physiological performance and incremented the yield of plants • No change in photosynthetic activity • Plants grown from infected seeds did not trigger oxidative stress due to the reduction of pathogen incidence in seeds treated with cold plasma • Vegetative growth revealed a similar pattern for plants grown from treated seeds than that found for the healthy control • Infected control, by contrast, showed clear signs of damage	[264]
Family: Fabaceae soybean *Glycine max* (L.) Merr	Needle to plane DBD at 0–25 kV operating at 50 Hz FG: N_2 and O_2 GF: 6 NL min^{-1} TT: 2 and 3 min	• Complement to [264] • Biometrical parameters of 40-d-old plants grown from plasma-treated seeds • Significant increase in shoot length of seedlings from O_2 plasma-treated seeds was observed, while both applied FGs led to an increase in root length and total leaf area • Elevated nitrogenase activity in nodules growing on plants of plasma-treated seeds	[265]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae soybean *Glycine max* (L.) Merr	Needle to plane DBD at 0–25 kV and at 50 Hz FG: N_2 and O_2 GF: 6 NL min^{-1} Power: 16 W TT: 2 min for N_2 and 3 min for O_2	• Complement to [264, 265] • Changes in phenotypes but no significance • Plasma treatment with both FGs induced DNA methylation changes with respect to the Control plants, with higher differentiation at 20 days after sowing than at 6 days after sowing • Epigenetic variability and the phenotypic variability correlated only at 20 days after sowing	[266]
Family: Fabaceae soybean *Glycine max* (L.) Merr	Needle array DBD FG: O_2 and N_2 gas GF: 6 NL min^{-1} Power: 65 W and 85 TT: 60–180 s	• All plasma treatments had a significant stimulatory effect on seed germination and vigor • CAT, SOD and guaiacol peroxidase: high CAT activity and GSH content exhibited by infected seeds (IC) suggested that they coped with the oxidative damage • Reduction in WCA after treatment, positive correlation between seed hydrophilicity and lipid peroxidation of seed coats • ABA levels were decreased, and auxin level was increased	[264]
Family: Fabaceae soybean *Glycine max* L. cv. Nížina	DCSBD at 20 kV and 14 kHz FG: air, O_2, N_2 GF: 3 L min^{-1} TT: 30, 60, 90, 120 s	• Positive effect on seed germination for O_2 60, 90 s, no significant increase for air and N_2 • Seedling length was elevated for N_2 plasma-treated seeds at 30 s and for air plasma-treated seeds at 60 and 90 s • Longer N_2 plasma TTs significantly inhibited succinate dehydrogenase activity, but stimulated lactate and alcohol dehydrogenase activities, suggesting anoxygenic metabolism • Significant DNA damage was found for N_2 plasma • Higher level of DNA damage was also detected in the negative control (untreated seeds), which might be associated with the age of seeds followed by their lower germination capacity	[335]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae soybean *Glycine max* (L.) Merr	Needle to plane DBD at voltage from 10.8 to 22.1 kV FG: Ar GF: 2 L min^{-1} Power: 3.4 to 15.6 W TT: 12, 24, 48, 60, 120, 180 s	• 2 min of exposure duration, max. soybean sprout growth was obtained at 17.3 kV, but decreased with further increase in plasma potential till growth is eventually inhibited at >21.2 kV • Germination and production rates of soybean sprouts exposed to plasma at 22.1 kV for 1 min showed the highest increases compared with those of the control group, but longer plasma exposure duration of 2 min had significant contrary effects • A slightly higher germination rate and enhanced root and shoot growth; changes in DNA methylation level, an increased SOD, POD and CAT enzyme activity	[382]
Family: Lamiaceae sweet basil *Ocimum basilicum* L.	Surface DBD FG: air Power density: 80 mW cm^{-2} TT: 10–600 s	• SEM only "etched" at microplyar region, no alterations on other surface regions • SEM-EDX, increase in relative O-content • Swelling behavior, seed size increase during imbibition • Improved seed germination, growth parameters of seedlings (total length, weight, leaf extension) considerably increased compared to the controls."	[7]
Family: Lamiaceae sweet basil *Ocimum basilicum* L.	Volume DBD FG: humid air GF: 7 slm Energy density: 151 kJ m^{-3} for seed-filled system TT: 10, 20, 30 s, 1, 3 min	• Elevated germination at all treatments parameters • Significant increase in seedling weight at 30 s and 3 min	[8]
Family: Lamiaceae woodland sage *Salvia nemorosa* L.	Planar DBD FG: Ar GF: 1–2 slm Power density: 0.84 W cm^{-2} TT: 80 and 100 s	• Significant increase in shoot, root fresh weight, root length for 80 s more pronounced than 100 s	[91]
Family: Lamiaceae lemon balm *Melissa officinalis* L.	DBD at 13 kHz and 10 kV FG: Ar GF: 2 L min^{-1} Power density: 0.84 W cm^{-2} TT: 50, 90, 120 s	• 50 s treatment significantly improved the stem length • Plasma significantly improved root length at 50 and 90 s TT • Toxicity of zinc oxide and selenium was reversed after plasma treatment • Improved the total plant fresh mass for 50 and 90 s TT	[14]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Malvaceae cotton *Gossypium hirsutum* L. var. Sicot 74BRF	Needle-shaped DBD at 1 kHz sine wave with 38 kVpp for air and 11 kVpp for argon FG: Ar, air GF: 1 L min^{-1} TT: air 3, 27 min. dry air, Ar 81 min	• 27 min plasma treatment air significantly increase water absorption of seed, improves warm germination, metabolic chill test germination and chilling tolerance in cotton • Effect stable for 4 months	[66]
Family: Malvaceae garden tree-mallow *Lavatera thuringiaca* (L.) Vis (L.) Vis	DBD plasma jet at 17 kHz FG: N_2, He GF: 1.6 dm^3 min^{-1} of helium with 0.03 dm^3 min^{-1} of nitrogen Power: mean power of 6 W TT1, 2, 5, 10 and 15 min	• Increase in germination speed and max. germination after plasma treatment especially for 1, 5 min • No significant decrease in WCA	[260]
Family: Malvaceae garden tree-mallow *Lavatera thuringiaca* (L.) Vis var. Uleko	Gliding arc at 50 Hz, applied RMS voltage amounted to 680 V (max. 3.8 kV), RMS current and mean power from the mains were 33 mA FG: N_2 GF: 8 L min^{-1} Power: 40 W TT: 1, 2, 5, 10, 15 min	• Highest germination parameters were obtained for seeds stimulated with plasma for the exposure times of 2 and 5 min • Decrease in germination • WCA no significant decrease • Longer exposure of seeds to plasma resulted in affecting the deeper zone of cuticle and damage or fracture of some parts of the cuticle	[259]
Family: Pinaceae common pine *Pinus sylvestris* L. black pine *Pinus nigra,* J.F. Arnold mountain pine *Pinus mugo* Turra	DBD FG: air Power: density 75 W cm^{-3} TT: 1, 3, 5, 10, 30, 60 s	• Trends but non- significant elevated germination speed and max. germination, as well as early growth • Decrease in mean seedling length for black pine for 60 s plasma TT	[308]
Family: Pinaceae black pine *Pinus nigra* J.F. Arnold	DCSBD at 14 kHz sinusoidal high voltage, amplitude of up to 20 kV peak-to-peak FG: air TT: 1, 3, 5, 10, 30, 60 s	• WCA: significant decrease • Significant elevated germination for 3 s TT after two days • 60 s plasma treatment lowered germination • Early growth: 30 and 60 s treatments had significantly smaller dry seedling weight than the other samples • 5 s samples had the heaviest seedlings	[309]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Piperaceae pepper *Capsicum annuum* L. and Family: Cucurbitaceae melon *Cucumis melo* L.	Volume DBD at 20.7 kV peak-to-peak, fAC = 5 kHz) FG: air GF: 1 slm TT: 2–300 s	• Decrease in germination for pepper seeds from 15 s onwards, for melon from 100 s onwards, strong decrease at 300 s • Decrease in WCA for pepper and melon, • WU for 60 s treatment small differences for the first 60 min of imbibition • Element ratio: pepper seeds, O:C ratio gradually increased with increasing the plasma TT, the O:C ratio of melon seeds increased only for short TTs < 5 s, and plasma treatment for >5 s led to a profound decrease in the O:C ratio	[116]
Family: Poaceae barley *Hordeum vulgare* L. cv. Maltz	DCSBD FG: air, O_2 or N_2 GF: 3 Lpm Power density: surface (1–3 W $cm^{-2)}$ and volume (~80 W cm^{-3}) Power: 400 W TT: 10, 20, 30, 60, 180, 300 s	• Stimulating effects on germination for 10 s plasma TT with all feed gases but significant decreased germination for >20 s plasma, • Slight positive effects of plasma treatment on seedling growth (lengths and weight of shoot and root) were observed for all applied FGs and TTs ≤ 20 s, • Significant increase in DNA double-stand breaks for 60 s air plasma treatment revealed genotoxic potential of plasma treatment	[267]
Family: Poaceae rice *Oryza sativa* L. var. Zhu Liang You 06, var. Qian You No. 1	Non defined non-thermal plasma generator at 10 kV, 2 kHz FG: N_2 (79%) and O_2 (21%) GF: 3 L min^{-1} TT: 1 min	• Seed germination and seedling growth enhanced • Photosynthetic pigments, photosynthetic gas exchange, and chlorophyll fluorescence improved by cold plasma treatment	[311]
Family: Poaceae rice *Oryza sativa* L. var. NSCI RC298	Plasma jet at AC, 232 V and 1.99A input FG: air GF: 25 cfm Power: 450 W TT: 1, 2, 3 s	• No to small change in germination speed nor max. germination • Seedling length decease for 1 s, increase for 2 and 3 s	[262]
Family: Poaceae wheat *Triticum aestivum* L. var. Buryatskaya Ostistaya, var. Buryat BRIA	Atmospheric pressure glow discharge (APGD) FG: Ar Power: 5 W TT: 30 s	• WCA strongly decreased after plasma treatment • Elevated germination, no quantification presented	[22]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae wheat *Triticum aestivum* L. var. Julius Family: Poaceae barley *Hordeum vulgare* L. var. Kosmos	Volume DBD FG: Ar GF: 4 slm Power density: 53.5 mW cm^{-3} TT: 10–60 s	• Cumulative germination was enhanced after 27 h of germination for wheat seeds treated from 10 to 60 s, • Barley seeds respond to the short plasma TTs with increased germination of after 24 h of germination • Decrease in the water contact angle • WU by seeds was moderately increased after 2 h of imbibition • Increase in hydrophilic functional groups being detected by x-ray photoelectron spectroscopy	[38]
Family: Poaceae barley *Hordeum vulgare* L. var. Saechal (waxy hull-less barley) and var. Saessal (non-waxy hullless)	DBD FG: N_2, air GF: (3 lpm) mixed with bubbled air (0.1 lpm, O_2 0.65% containing) as feed gas Power: 400 W TT: 10, 20, 40 and 80 s	• Growth of plasma-treated barley was increased • GABA content of plasma-treated Saechal barley was slightly increased under no germination process, while DPPH activity was decreased at the same condition • Denser and longer roots and higher shoots in plasma-exposed seedlings	[256]
Family: Poaceae brown rice *Oryza sativa* L. six cultivars	DBD driven by RF FG: Ar GF: between 18, 20 24 ml min^{-1} Power: 100, 135, 170, 200 W TT: 25, 50, 75, 100, 150, 200, 300 s	• SEM analysis revealed eroded seed surfaces with softer and smoother structures after plasma treatment • Germination percentage and seedling biomass parameters (root length and seedling length) were increased for applied plasma powers $\leq$170 W and all gas flow rates with max. values for seeds treated with plasma at 135 W and gas flow rates of 20–24 ml min^{-1} • Applied power of 200 W and all applied gas flow rates resulted in inhibitory effects on seed germination and biomass parameters • Exposure times up to 150 s at undefined plasma power and gas flow rates, resulted in increased values for germination and seedling lengths • Similar positive effects on germination and seedling growth were observed for 5 further brown rice cultivars, • Within the first 48 h after germination, the total content of phenolic compounds, of vitamin E and of γ-oryzanol significantly increased in all six rice cultivars, while the antioxidant activity was not significantly altered	[373]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae maize Zea *mays* L.	DCSBD FG: air Power: 100 Wcm^{-3} TT: 60 and 120 s	• 6-day old seedlings obtained from 60 s plasma treatment showed >10% increase in root length, root fresh and dry weight • 120 s plasma treatment had inhibitory effects on seedling growth with shorter root lengths and lower weight • CAT, G-POX, SOD and DHO in seedlings of plasma-treated seeds were differently affected	[110]
Family: Poaceae maize Zea *mays* L. cv. Ronaldinio	DCSBD FG: O_2, N_2, air GF: 3 L min^{-1} Power: 400 W input TT: 30, 60, 90, 120, 180 and 300 s	• No change in germination for 30/60 s • Prolonged treatment >90 s = negative impact on the germination, growth, and production indexes • No change in imbibition • WCA: significant reduction form 30 s onwards	[115]
Family: Poaceae maize *Zea mays* L. cv. Ronaldinio	DCSBD at 14 kHz sinusoidal high voltage with an amplitude up to 20 kV peak-to-peak, input power of 400 W FG: air Power density: 80 W cm^{-3} TT: 15, 30, 60, 120, 180, 240, 300 s	• WCA strong decrease • Increase in wettability, resulting in a better WU and in an enhancement of growth parameters • WU for 60 and 300 s treated seeds: the most significant difference was visible after the first hour. Samples plasma-treated for 60 and 300 s absorbed more water than control samples • Shorter TT (about 60 s) had beneficial effects on the growth parameters of seedlings • No significant response of changes of germination found at TT of 60 and 120 s in comparison to the control • Greater reduction in germination was observed at the exposure time of 240 s • After 300 s nearly complete loss of germination • TT of 60 s stimulated root length by 12% and shoot length increased • Plasma treatment of maize seeds affected germination and growth of primary roots (length, fresh and dry weight production) but does not significantly affect root anatomy and morphology	[380]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae wheat *Triticum aestivum* L.	Surface DBD FG: air GF: 1 L min^{-1} Power: 2.7 W TT: 15 min	• WCA: strong decrease • WU: significantly accelerated • Little effect on the germination rate while a substantial positive impact on growth parameters (roots and shoot lengths, dry weight of roots) of 4 days old seedlings • Increased root-shoot-ratio	[71]
Family: Poaceae wheat *Triticum aestivum* L.	Planar DBD at 13.0 kV, 50 Hz FG: air GF: 1.5 slm TT: 4 min	• Germination potential and germination rate increased, and the root length and shoot length of the wheat seedlings also increased • Increased proline and soluble sugar levels in normal water conditions and in seedlings exposed to drought conditions • Decrease in MDA content in seeds under drought stress • Increase in SOD, POD and CAT enzyme activity	[99]
Family: Poaceae wheat *Triticum aestivum* L. cv. Xiaoyan 22	Planar DBD at 50 Hz, 9–17 kV FG: air GF: 1.5 slm TT: 4 min	• Germination rate, germination potential, root length, and shoot length of the wheat seedlings increased after DBD treatment at 11.0 kV	[101]
Family: Poaceae wheat *Triticum aestivum* L.	Packed-bed at 100 Hz and 83 kHz voltage at 8 kV FG: air TT: 3, 10, 30 s	• Elevated germination for all TTs • No effect on leaf and root length, dry matter	[161]
Family: Poaceae wheat *Triticum aestivum* L. cv. Xiaoyan 22	Planar DBD FG: air GF: 1.5 slm Power: 1.5 W TT: 1 – 13 min	• Time of germination accelerated • Growth accelerated • For 4 min plasma TT, activity of antioxidant enzyme increased • Increased root and shoot growth • Increase in proline and soluble sugar levels	[179]
Family: Poaceae wheat *Triticum aestivum* L.	DBD at 80 kV and 50 kHz FG: air TT: 5 and 20 min	• WCA was strongly reduced for direct plasma and both TTs, but not for indirect treatment mode • No effect on germination for 5 min TT, but reduction in germination for 20 min TT	[189]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae wheat *Triticum aestivum* L.	DBD at 80 kV and 50 kHz FG: air TT: 30, 60, or 180 s	• WCA was strongly reduced • Treatments of 30–60 s significantly enhanced germination rate and showed positive effects on seedling growth • Changes in seed pH and total titratable acidity, as well as nitrites, nitrates, and MDA contents • No significant increase in WU for both direct and indirect plasma treatment • Retention time 24 h before usage: significant elevated WU 60, 180 s	[190]
Family: Poaceae wheat *Triticum aestivum* L.	Plasma jet at 2.6 kV FG: N_2 GF: 14 L min^{-1} TT: 2, 4, 6, 8, 10 min	• After 2 h elevated WU after plasma treatment • No difference in WU after 12 h of soaking • Significant increase in max. germination • Significant increase in shoot, root length, fresh and dry weight after 10 days of growth	[192]
Family: Poaceae wheat *Triticum aestivum* L.	DBD at 13 kV and 50 Hz FG: O_2, air, Ar, N_2 GF: 1.5 slm TT: 4 min	• SEM analysis revealed etching effects on the seed coat for air, N_2 and Ar plasma-treated seeds, which affected the hygroscopicity and permeability of the wheat seed • Germination potential significantly increased by after 4 min of the air, N_2 and Ar plasma treatments • Shoot and root length was increased but not after O_2 plasma treatment	[207]
Family: Poaceae wheat *Triticum aestivum* L.	Planar DBD at 16 kHz and 20 kV FG: He GF: 5 slm Power: 30 W TT: 10–900 s	• Decrease in WCA • Surface analysis revealed a remarkably enhanced wettability of plasma-treated seeds due to the insertion of oxygen containing functionalities on their surface • Short plasma exposures were shown to enhance WU and accelerate seed germination, especially under water-scarcity conditions at TT < 200 s • WU accelerated after plasma treatment under low water availability for the first 4 h of imbibition • Long plasma exposures damaged the outermost layers of the pericarp due to a pronounced oxidative etching effect	[220]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae wheat *Triticum aestivum* L.	Coaxial DBD at 10 Hz FG: Ar/He GF: 2 slm Power: 1-10 W TT: 3 to 30 min	• Faster germination acceleration and a lower WCA for Ar plasma treated seeds	[240]
Family: Poaceae wheat *Triticum aestivum* L.	DBD at 22.5 kHz and 10 kV FG: air Power: 30 W TT: 2, 5, 10 s RF Jet at 13.56 MHz and 10 kV FG: Ar GF: 4 L min^{-1} Power: 30 W TT: 15–300 s	DBD: • Enhancement of hydrophilicity of the seed surface and reduction of WCA • Ability of water imbibition by wheat seeds increased • Significant decrease in mean germination time for all plasma treatments • No change in root, shoot length Jet: • Decrease in WCA • Significant decrease in mean germination time for 2 s plasma treatment • Significant elevated mean germination time for >50 s • Elevated root length, dry weight >50 s TT	[347]
Family: Poaceae wheat *Triticum aestivum* L. cv. Eva	DBD at 14 kHz and at 20 kV peak to peak FG: air Power density: 70–100 W cm^{-3} TT: 10–80 s	• WU slightly tended to increase with increasing TT • Germination percentage 10 days after germination was significantly higher for TTs of 20–40 s • Significant positive effects on dry weight and vigor of 10 days old seedlings were observed for 30 and 40 s plasma-treated seeds • Plasma TTs of 70 and 80 s had significantly negative effects on seed germination and seedling growth	[379]
Family: Solanaceae pepper *Capsicum annuum* L. var. 'Superhot'	Plasma jet at 25 kHz FG: Ar GF: 3 slm Power: 0.41–0.61 W TT: no treatment time indicated	• Significant increase in germination speed for all plasma treatment parameters after 1 week • No change in max. germination (after 2 weeks) • No significant difference for lengths of seedlings and canopy and number of leaves	[341]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Solanaceae pepper *Capsicum annuum* L.	Planar DBD at 11 kV FG: Ar GF: 1–2 slm Power density: 0.84 W cm^{-2} TT: 60 and 120 s	• Plasma treatment of 1 min had an improving effect on the shoot and root lengths as well as total leaf area • Plasma treatment of 2 min had an adverse effect. significantly impaired growth and hence reduced the total biomass • Alterations in stem diameter and differences in tissue patterns (especially in the vascular system) occurred, and were mainly dependent on the plasma exposure time and/or the presence of hormones	[288]
Family: Solanaceae pepper *Capsicum annuum* L.	DBD at 11 kV and 23 kHz FG: Ar Power density: 0.84 W cm^{-2} TT: 60 and 120 s	• Plasma-treated seeds seemed to gernate earlier according to visual observation • 35 days old plants of 120 s plasma-treated seeds displayed slight but significant increased biomass parameters (plant fresh weight, total leaf area) and biochemical parameters (chlorophyll and carotenoid content) • For both plasma TTs, a significant increase in POD and PAL activities and increased phenolic contents in leaves and roots were found in 35 days old seedlings	[125]
Family: Solanaceae tomato *Lycopersicon esculentum* Mill hybrid Belle F1	Coaxial DBD at 13–17 kV and 50 Hz FG: air GF: 15 slm Power: 0.55–1.43 W TT: 5, 7, 13, 30, 45 min	• Germination percentage after 5 days of germination was higher for all applied plasma TTs (5, 30, 45 min) at 17 kV and 1.43 W • 5 days old seedlings from 5 and 30 min plasma-treated seeds displayed significantly higher root and shoot lengths and higher plant dry weight while seedlings from 45 min plasma-treated seeds were unaffected, all plasma treatments at different applied voltages and TTs (13 kV and 13 min, 15 and 7 min, 17 kV and 5 min) resulted in faster germination, increased biomass parameters (fresh and dry weight) and higher root length with higher branches of seedlings monitored up to 20 days of growth • Shoot lengths of 12 days old seedlings were only increased for 17 kV and 5 min plasma-treated seeds while root-to-shoot ratio increased for all applied plasma treatment parameters	[196]

(continued)

Table 6.4 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Tropaeolaceae nasturtium *Tropaeolum majus* L	DBD at 20 kV and 16 kHz FG: He with air impurity GF: 5 L min^{-1} Power: 30 W TT: 10, 30, 120, −300 s	• SEM analysis revealed no changes in seed surface morphology after 300 s plasma treatment • Analysis of seed coat by XPS revealed a relative increase of O, N and K elements and a relative decrease of carbon for all plasma TTs • FTIR-ATR analysis of the seed coat revealed no change in chemical composition and a decrease in OH band intensity in plasma treated seeds was attributed to water loss from the seed coat during plasma exposure • Weight loss of seeds increased with increasing plasma TTs due to loss of water and rising temperatures during plasma exposure • WCA of the seed surface was significantly decreased as observed for 30 s plasma-treated seeds • WU was accelerated for 30 and 300 s TT and was unchanged for 10 s plasma-treated seeds • Germination speed and Germination of plasma-treated seeds was lower during the 12 h observation under sufficient water supply conditions, while seeds treated with plasma for 10 and 30 s displayed better germination under conditions of low water supply • Germination of 300 s plasma-treated seeds was impaired under all water supply conditions	[219]

ABA—abscisic acid; APGD—atmospheric pressure glow discharge; APX—ascorbate peroxidase; CAT—catalase; cv.—cultivar; DBD—dielectric barrier discharge; DCSBD—diffuse coplanar surface barrier discharge; DPPH—2;2-diphenyl-1-picrylhydrazyl; FG—feed gas; GA—gibberellin; GA3—gibberellin A3; GA7—gibberellin A7; GABA—γ-aminobutyric acid; GF—gas flow rate; GR—glutathione reductase; GSH—glutathione (γ-glutamyl-cysteinyl-glycine); MDA—malondialdehyde; nZnO—zincoxide; PAL—phenylalanine ammonia lyase; POD—peroxidase; PPO—polyphenol oxidase ROS-reactive oxygen species; SEM–EDX—scanning electron microscope-energy dispersive X-ray spectroscopy; SOD—superoxide dismutase; TT—treatment time; WCA—water contact angle; var.—variety; WU—water uptake; XPS—X-ray photoelectron spectroscopy

Table 6.5 Effects of low-pressure plasma on plant seeds

Plant species	Plasma parameters	Observed effects	References
Family: Amaranthaceae lamb's quarters *Chenopodium album* agg	Microwave discharge P: 40 mbar FG: Ar/O_2 and Ar/N_2 Power: 100 W TT: 6–48 min	• Germination tests revealed no changes in seed viability or medium germination time even after longest plasma TT	[304]
Family: Amaranthaceae Quinoa *Chenopodium quinoa*, Willd. var. Atlas	DBD at 1 kHz and 8.2 kV P: 500 mbar FG: dry air Power: 6.4 W TT: 10, 30, 60, 180 and 900 s	• XPS: decrease in C % and increase in O % and N %, • WU slightly accelerated • SEM images revealed etching and damage of seed surface for longest TT • Significant improved germination for all treatment times longer than 10 s	[96]
Family: Amaranthaceae Quinoa *Chenopodium quinoa*, Willd. var. Atlas	RF at 13.56 MHz P: 0.1 mbar, FG: dry air Power: 15 W TT: 10, 30, 60, 180 s	• XPS: decrease in C % and increase in O % and N % • WU slightly accelerated • SEM images revealed etching and damage of seed surface for longest TT • Shortest TT of 10 s resulted in most stimulating effect on germination while 180 s treatment slowed down germination	[96]
Family: Amaranthaceae spinach *Spinacia oleracea* L. var. Beiouzhizun	Magnetized arc plasma P: 10–20 Pa FG: air Power: 400 W TT: 0.45 s	• Plasma treatment resulted in higher germination rates with increased germination percentage after 7 and 21 days of observation time	[310]
Family: Apiaceae Sprague Ajwain *Trachyspermum ammi* (L.)	RF at 13.56 MHz P: 1 Pa FG: air Power: 50, 80, 100 W TT: 2 min	• WCA significantly decreased after plasma exposure at 50 W • 50 W plasma treatment resulted in significantly higher cumulative germination values for 7 days germination time and improved germination index while 100 W plasma treatment resulted in germination performance similar to untreated seeds • Root length of seedlings significantly increased for 50 W plasma treated seeds	[92]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Asparagaceae wild asparagus *Asparagus acutifolius* L.	RF at 13.56 MHz P: 800 mTorr FG: O_2, N_2 and O_2/N_2 mixture (20%/80%) Power: 50 W TT: 1, 15, 30 min	• 1 min O_2/N_2 and N_2 plasma and 15 min N_2 plasma had positive effects on germinability with reduced T_{50} value • Oxygen plasma led to negative effects on seed germination parameters (germinability, mean germination time, 50% time of germination) • All other plasma treatments resulted in higher T_{50} values and mean germination times	[188]
Family: Asteraceae artichoke *Cynara scolymus* var. *scolymus* L.	RF at 13.56 MHz P: 1.8 Pa FG: N_2 Power: 10 W TT: 3, 10, 15 min	• SEM analysis revealed occurrence of cracks and holes even after 3 min TT • WCA drastically reduced even after 3 min TT and complete wettability was achieved after 15 min plasma treatment • WU significantly accelerated • Germination parameters (rate, vigor index) and seedling growth (root and shoot length) positively affected for all TTs • 10 and 15 min TT led to significant root and shoot dry weight • POD and CAT activities slightly increased after the 15 min plasma treatment	[119]
Family: Asteraceae purple coneflower *Echinacea purpurea* (L.) Moench	RF at 5.28 MHz P: 60 Pa FG: air Power density: 0.35 W cm^{-3} TT: Power density: 0.35 W cm^{-3}	• All treatments resulted in faster germination without change in final germination percentage • Plasma treatment resulted in increased plant height, leaf number, and root weight • Content of vitamin C and phenolic acids as well as radical scavenging activity leaf extract significantly increased	[210]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Asteraceae safflower *Carthamus tinctorium* L.	RF at 13.56 MHz P: 1.6 and 16 Pa FG: Ar Power: 20 W TT: 30 and 130 min	• SEM analysis displayed surface modification at the hilum • Increased germination rate after 10 days for plasma treatment at 20 W for 30 min and at 16 Pa for 130 min	[69]
Family: Asteraceae sunflower *Helianthus annuus* (L.)	RF at 5.28 MHz P: 200 Pa FG: air Power density: 0.35 W cm^{-3} TT: 2, 5, 7 min	• No significant trend in changes of germination characteristics (final germination percentage, median germination time) with increasing TTs could be observed • Plasma treated seeds stored for 4 days displayed higher GA3 levels • 7 min plasma treated seeds had increased levels in IAA while ABA levels were unchanged • An increase of ABA in 2 min plasma treated seeds and a decrease in 5 min plasma treated seeds could be observed • Biomass parameters (lengths and weight of roots and shoots, leaf weight) of seedlings 2 weeks after sowing were not improved for different TTs • Leaf protein expression data from 2 weeks old seedlings revealed long-term effects of plasma treatment on photosynthesis related metabolism and regulation	[209]
Family: Brassicaceae radish *Raphanus sativus* L.	RF at 13.56 MHz P: 40 Pa FG: air Power: 50 W TT: 10–90 min	• All TTs led to increased seedling lengths observed 3 days of germination • 20 min treatment displayed the highest values and germination was significantly accelerated	[109]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Brassicaceae radish *Raphanus sativus* L.	RF at 13.56 MHz P: 20, 40, 80 Pa FG: Ar and O_2 Power: 60 W TT: 5, 15, 30, 60 min	• Radish seedling lengths were increased for all TTs at 80 Pa • 30 min plasma treatment at 40 or 80 Pa resulted in increased radish seedling lengths as well, while seedling length from 20 Pa plasma treated seeds were unchanged	[233]
Family: Brassicaceae radish *Raphanus sativus* L.	RF at 13.56 MHz P: 100 Pa FG: O_2 and N_2 Power: 50 W TT: 30, 60, 90, 120 min	• SEM analysis revealed no alteration of surface structures even after 120 min treatment time for O_2 plasma treated seeds • FTIR-ATR displayed no chemical modifications after O_2 plasma treatment • Accelerated seedling growth of O_2 plasma treated seeds monitored after 7 days • No effects on seedling growth after N_2 plasma treatment of seeds for 30 min • No effects were observed for seed germination	[158]
Family: Brassicaceae rapeseed *Brassica napus* L. cv. Zhongshuang 7 and11	RF at 13.56 MHz P: 150 Pa FG: He Power: 100 W TT: 15 s	• WCA was significantly decreased after plasma exposure of seeds • Under drought stress conditions, germination parameters (germination time, rate, germination and vigor index) were improved while maximum germination and median germination were unaffected • Biomass parameters (shoot and root lengths, dry weights and lateral root number) of 7 days old seedlings were significantly increased for both cultivation conditions (drought stress and non-stress) • Under drought stress conditions, protein and soluble sugar contents and activity of antioxidant enzymes (CAT, SOD) were significantly increased in seedlings, while MDA contents were decreased	[178]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Brassicaceae rapeseed *Brassica napus* L.	DBD at 3 kV and 4.5 kHz P: 10 Torr FG: Air/O_2 (Air: 60%, O_2: 40%) and Ar/Air (Ar: 60%, Air: 40%) Power: 30 W TT: 90 s	• Germination of plasma treated seeds accelerated after 3 days of germination time with higher α-amylase activity in germinating seeds • Activities of SOD and CAT accelerated for Ar/Air plasma treated seeds, while APX activity was unaltered • Shoot dry weights increased and shoot lengths were significantly higher in 5 days old seedlings of plasma treated seeds • Biomass parameters of roots unaltered • No changes in H_2O_2 content detected in germinating seeds or shoots and roots of seedlings • Seedlings from Air/O_2 plasma treated seeds exhibited significant higher chlorophyll and protein contents in shoots and tremendous higher APX activity and mRNA level in roots • SOD and CAT activities in roots and shoots and APX activity in shoots not affected in seedlings of plasma treated seeds	[129]
Family: Brassicaceae rapeseed *Brassica napus* L.	DBD at 5.7 kHz and 8.7 kVpp P: 300 mbar FG: Ar TT: 15 s	• Higher germination percentage observed after 24 and 48 h	[297]
Family: Brassicaceae rapeseed *Brassica napus* L. cv. Zhongshuang 9	RF at 13.56 MHz P: 150 Pa FG: He Power: 60, 80, 100, 120 W TT: 15 s	• WCA decreased with increasing applied power • WU significantly accelerated after plasma treatment • Germination characteristics (germination rate, index, vigor) improved for all applied powers • Increased dry weight more prominent for roots accompanied by increased root length for seedlings • Field experiments showed that plasma treated seeds resulted in plants with higher pod numbers per plant and 1000 seed weights • 100 W plasma treatment resulted in best results for studied germination and field parameters	[176]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Cannabaceae hemp *Cannabis sativa* L. cv. Finola cv. Bialobrzeskie cv. Carmagnola	Microwave plasma discharge at 2.45 MHz P: 140 Pa FG: Ar, O_2 TT: 3, 5, 10 min	• Effects of plasma treatments had different effects on germination depending on cultivar and observation times of 3, 4 and 5 days • No effects on germination were observed for Finola, while negative effects were observed for Bialobrzeskie and Carmagnola • All cultivars respond negatively to microwave plasma treatment resulting in reduced seedling growth with smaller seedling weights	[306]
Family: Cannabaceae industrial hemp *Cannabis sativa* L. cv. Futura 75	RF at 5.28 MHz P: 200 Pa FG: air Power: 8.4 W TT: 5 min	• Maximum germination and median germination time was significantly improved while uniformity of germination was unchanged under laboratory conditions while no stimulation of germination under field conditions could be observed • Biomass parameters of 4 months grown plants were either negatively affected for female plants (shoot weight) or positively affected for male plants (shoot lengths and weight) • Number of inflorescences per female plant was unaltered • Cannabidiolic acid levels in leaves and inflorescences of female plants were markedly decreased	[131]
Family: Fabaceae alfalfa *Medicago sativa* L. cv. Zhongmu 6	RF at unknown frequency P: 130–160 Pa FG: Air/He mixture Power: 20–280 W TT: 15 s	• Effect of different plasma treatments on the germination simulated drought stress conditions was investigated. PEG 6000 with 5, 10, and 15% (w/w) • Plasma effects on germination parameters (potential, rate, index) and seedling parameters (root and shoot length, vigor index) under non-stressed and under different stress levels depended on applied power, with positive effects up to 140 W and partially negative effects at higher power values • 40 W was denoted as the most effective treatment power for improved germination and seedling growth under different germination conditions simulating drought stress	[80]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae black gram *Vigna mungo* (L.) Hepper cv. Barimash 3	DBD at 4.5 kHz and 5 kV P: 400 Torr FG: air Power: 45 W TT: 20, 40, 60, 90, 120, 180 s	• SEM analysis revealed smoothening of seed surface structure with increased TT • WU values significantly increased for TTs with max. values at 180 s • Germination at day 3 significantly higher for all TTs • Biomass parameters (shoot and root lengths and dry weight) tended to increase at all TTs, with significant higher values for shoot dry weight • Chlorophyll content of seedlings from 40–189 s plasma treated seeds had significant higher values • H_2O_2 content in leaves and roots were significantly increased for 90–180 s plasma treated seeds • NO content in leaves and roots tended to increase • Total soluble protein content in roots and leaves significantly increased for TTs > 60 s • Total soluble sugar content increased in leaves of plasma treated seeds >40 s • APX activity in leaves and roots (120 s, 180 s TT) and CAT activity in leaves (180 s) and roots (90–180 s) were significantly accelerated • SOD activity was unchanged in leaves and roots of plasma treated seeds	[31]
Family: Fabaceae common bean *Phaseolus vulgaris* L.	RF at 13.56 MHz P: 5, 15, 20 Pa FG: O_2 Power: 400 W TT: 0.5, 3, 10 s	• Increased surface roughness (SEM analysis), • WCA: drop down from 85° to 0°, but hydrophobic recovery observed up to 42° after 30 h storage for 0.5 s and up to 15° • XPS: decrease in C % and increase in O % • WU accelerated • Depending on TT and applied power germination performance was affected positively and negatively • Despite this, radicle lengths of seedlings were increased with increased TT and power values	[281]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae common bean *Phaseolus vulgaris* L.	RF at 10 MHz P: 0.067 FG: air Power: 20 W TT: 2 min	• Weight of seeds clearly decreased with increasing TT up to 5 min • WCA of seed surface significantly decreased after plasma treatment, while WCA of surfaces from underlying tissue layers (mesotesta, cotylodones) were unaffected • Exposure of uncovered mesotesta and cotylodones to plasma resulted in a decrease in WCA • WU significantly accelerated for seeds with and without sealed micropyle • WU visualized by bromophenol blue dye revealed proved the plasma effect and the role of the micropyle structure during imbibition • Plasma treatment slightly accelerated germination but did not change final germination percentage	[35]
Family: Fabaceae lentil *Lens culinaris* Medik		• SEM analysis revealed no alterations of seed surfaces after 15 s plasma treatment of lentil, bean and wheat seeds • TOF-SIMS MS analysis of seeds revealed increase in nitrogen and oxygen containing groups of seed surface	
Family: Fabaceae common bean *Phaseolus vulgaris* L.	RF at 10 MHz P: 0.067 Pa FG: air Power: 20 W TT: 15 s – 2 min	• WCA was severely decreased for all plant species treated for 15 s, but WU was only slightly increased • Longer TTs did not increase wettability any further • WCA still decreased for one month stored seeds	[34]
Family: Poaceae wheat *Triticum* spec. L.		• Seed germination clearly accelerated for all plant species during different observation time (6 d for beans, 1 d for lentils and 12 h for wheat)	

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae mung bean *Vigna radiate* (L.) R.Wilczek	RF at 13.56 MHz P: 20 Pa FG: air Power: 40 and 60 W TT: 10, 15, 20 min	• WCA was significantly decreased after plasma treatment • WU values increased significantly • All plasma treatment parameters resulted in faster germination, and increased shoot lengths of seedlings • Higher reserve mobilization was accompanied with increased soluble protein and sugar content and higher amylase and phytase activities • Trypsin inhibition activity and phytic acid decreased in plasma treated seeds	[287]
Family: Fabaceae peanut *Arachis hypogaea* L. cv. Eyou 7	RF at 13.56 MHz P: 150 Pa FG: He Power: 60, 80, 100, 120, 140 W TT: 15 s	• WCA decreased significantly with plasma power >80 W • Maximum germination values were not changed for plasma treated seeds • Germination potential was significantly increased for 80–120 W plasma treated seeds, while germination rate was only significantly increased for 120 W plasma treated seeds • Median germination time and uniformity of germination were slightly improved for 80–120 W plasma treated seeds as well • Shoot dry weight of 7 days old seedlings tended to increase with applied power, but only 120 W plasma treatment resulted in significant changes • Shoot dry weight of 7 days old seedlings was significantly increased for 80–120 W plasma treated seeds • Field trials with 120 W plasma treated seeds revealed improved biomass parameters of shoots (height, diameter, branch number, dry weight, leaf area and thickness) and roots (dry weight) of growing plants • Nitrogen content and SPAD value was increased in leaves of field grown plants from plasma treated seeds • Yield parameters (pod number and weight, yield in kg ha^{-1}) were markedly improved	[177]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae red clover *Trifolium pratense* L. cv. Vyčiai cv. Sadūnai	RF at 5.28 MHz P: 200 Pa FG: air power density: 0.025 W cm^{-3} TT: 5 and 7 min	• 7 min treatment had positive effects on germination speed of both cultivars without effecting the maximum germination value • For both TTs lengths of 7 days old seedlings were decreased in cv. Sadūnai but were increased in cv. Vyčiai • Both cultivars tended to have higher seedling weight for TTs applied • Seed population of cv. Vyčiai harvested on different years respond differently to plasma treatment and showed that maximum germination values cannot be increased • Plants grown on the field experiment for 5 months displayed higher shoot biomass, but number of inflorescences was almost not altered • Protein content in leaves increased noticeably in both cultivars while other nutritional values were only slightly improved for cv. Vyčiai • Changes of major leaf isoflavone levels biochanin A and formononetin were dependent on vegetation stage • 5 min plasma treatment resulted in a significant increased biochanin A/formononetin ratios in both cultivars in vegetative stage, but ratios were decreased in flowering stage	[211]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae red clover *Trifolium pretense* L. cv. Arimaiciai	RF at 5.28 MHz P: 200 Pa FG: air Power density: 0.025 W cm^{-3} TT: 5 and 7 min	• Seeds with different coat colors (yellow, brown, and dark purple) displayed distinct responses to plasma exposure • Maximum germination and uniformity of germination was not altered for all seed populations, a significant decrease in median time of germination was observed for both TTs with faster germination for yellow seeds compared to dark purple and brown seeds • Changes in phytohormone levels (ABA, gibberellins, auxins, cytokinins, salicylic acid) of dry seeds after plasma treatment were dependent on seed color and did not correlate with germination kinetics • Seedling biomass parameters (lengths and dry weight) of 7 days old seedlings were positively affected for yellow seeds, while darker colored seeds did not respond significantly to plasma treatment • Root lengths of 5 weeks old plants from plasma treated yellow and dark purple seeds were positively affected while root weight was only significantly improved for dark purple plasma treated seeds accompanied with markedly increase in nodule number	[132]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae soybean *Glycine max* (L.) Merr cv. Zhongdou 40	RF at 13.56 MHz P: 150 Pa FG: He Power: 0, 60, 80, 100 and 120 W TT: 15 s	• WCA revealed increased seed surface wettability after plasma treatment • WU values tended to be higher for plasma treated seeds with maximum values observed for 80 W plasma treated seeds during 24 h of imbibition • Germination (potential, rate, germination and vigor index) parameters were either unaffected or moderately improved in case of 80 W plasma treated seeds • Biomass parameters (shoot and roots lengths and dry weight) of 7 days old seedlings were increased up to 100 W plasma treated seeds while 120 W treated seeds were unaffected • Plasma treated germinating seeds displayed higher seed reserve utilization and higher soluble sugar and protein contents	[175]
Family: Lamiaceae sweet basil *Ocimum basilicum* L.	RF at 13.56 MHz P: 0.40 mbar FG: mixture of O_2 (80%) and Ar (20%) Power: 30–270 W TT: 10 min	• 150 W with highest stimulatory effect on seed germination and seedling vigor • 150 W treatment with highest values for carbohydrate and protein content and catalase activity of 7 days old seedlings	[317]
Family: Moringaceae Moringa *Moringa oleifera* Lam	RF at 13.56 MHz P: 2 Torr FG: Ar Power: 100 W TT: 1, 5, 10, and 15 min	• SEM images reveled etching effects for all TT • Highest germination parameters (percentage, potential) were obtained for seeds treated for 1 min • Plant length and weight 1 and 5 min TT was larger than of untreated seeds • TT above 5 min have damaging effects on seeds viability	[64]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Paulowniaceae Empress tree *Paulownia tomentosa* (Thunb.) Steud	RF at 13.56 MHz P: 200 mTorr FG: air Power: 50, 100, 200 W TT: 1–40 min	• Depending on applied plasma power and TT times light-induced seed germination were either positively or negatively affected • A linear correlation for power intensity and exposure time on effects of germination could be observed • All TTs times at 50 W up to 30 min at 50 W resulted in an increase in germination percentage 10 days after imbibition • TTs < 10 min at 100 W had stimulatory effects on germination while TTs of 15 or 30 min inhibited germination • 1 min plasma treatment at 200 W stimulated seed germination while germination was impaired at longer TTs • UV shielding of seeds (glass cover of seeds) during plasma treatment at 100 W resulted in improved germination for 15 min TT, while 30 min plasma treatment still impaired germination	[389]
Family: Paulowniaceae Empress tree *Paulownia tomentosa* (Thunb.) Steud	RF at 13.56 MHz P: 100, 200, 400 mTorr FG: Ar, air Power: 100, W TT: 1–40 min	• At 100 W and 100 mTorr, air plasma TTs < 15 min had stimulatory effects on seed germination while plasma treatments at 100 W and 400 mTorr resulted in inhibition of germination when seeds were treated longer than 1 min • Compared to air plasma, Ar plasma inhibited germination by TTs > 1 min at 100 W and 200 mTorr • A clear markedly reduction in pH of water from imbibed plasma treated seeds was observed • The decrease in pH with a difference value of 3 was more pronounced for air plasma compared to Ar plasma • The nitrogen content of seeds was increased after air plasma treatment	[269]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Pinaceae Norway spruce *Picea abies* (L.) H. Karst	RF at 5.28 MHz P: 60 Pa FG: air Power density: 0.35 W cm^{-3} TT: 2, 5, 7 min	• Seed germination characteristics (final germination percentage, median germination time, dispersion of germination time) differed upon germination conditions in petri dishes and in peat substrate • Negative effects of all TTs on germination observed when seeds germinated in petri dishes for 17 days, while a positive effect on maximum germination of 7 min plasma treatment on germination was observed when seeds were germinated in peat substrate for 33 days • H_2O_2 content of seeds lowered for all TTs observed within 48 h after imbibition • Long-term effects of plasma treatment on biomass production revealed significant shoot lengths for 5 and 7 s plasma treated seeds 17 months after sowing • Depending on observation time during 17 months of growth after sowing, number of needles and number of branches tended to increase	[258]
Family: Poaceae brown rice *Oryza sativa* L. acc. Tai Keng 9, japonica cultivar	Glow discharge P: 800 Pa FG: air DC voltage: 1, 2, 3 kV TT: 10 min	• For all applied voltages, significant increased germination percentage, seedling lengths and WU values were recorded during 24 h observation time • Among all applied voltages, 3 kV treatment resulted in highest a-amylase activity, highest gamma-aminobutyric acid (GABA) levels, highest total phenol content and highest radical scavenging activity during several time points within 24 h of germination	[45]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae Maize *Zea mays* L. Family: Fabaceae lupine *Lupinus angustifolius* L. Family: Poaceae winter wheat *Triticum aestivum* L.	RF at 5.28 MHz P: 200 Pa FG: air Power density: 0.025 W cm^{-3} TT: 2, 4, 5, 7 min	• Germination percentage at day 10 of germination time and shoot lengths of 7 days old seedlings tended to increase for maize after plasma or vacuum treatment • Proline and phenolic contents were markedly increased in maize seedling roots and reduced in shoots after plasma treatment • Anthocyanin contents were increased in both shoots and roots of maize seedlings after plasma treatment • Yield of maize grown in the field tended to increase by 1.7% as a result of the plasma treatment • Germination percentage at day 10 of germination time were unaffected for all treatment conditions, while biomass parameters (shoot and root lengths) tended to increase after plasma or vacuum treatment of seeds • Wheat plants grown on field displayed higher phenolic contents during different growth stages • Yield of wheat grown in the field tended to increase by 2.3% as a result of the plasma treatment • Lupine shoot biomass of 7 days old seedlings was unaffected under all treatment conditions • Field trials with 4 min plasma treated lupine seeds resulted in plants having 26.8% higher yield with higher thousand seeds values	[84]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae oat *Avena sativa* L. Family: Poaceae wheat *Triticum aestivum* L.	Microwave discharge at 2.45 MHz P: 140 Pa FG: air Power: 500 W TT: 3, 5, 10, 20, 40 min	• SEM analysis of 10 min plasma treated oat revealed no changes of seed surface while plasma or vacuum treatment resulted in formation of cracks on wheat seed surface • Plasma treatment slightly improved wheat germination at day 4 of germination time but not at day 8 or 12 • Maximum germination of oat was reached at day 3 and was close to 100% for all TTs • Biomass parameters of seedling roots (lengths and weight) were either unchanged in oat and wheat or tended to have reduced values in wheat • Biomass parameters of seedling shoots (lengths and weight) displayed similar trends except an observed positive response in wheat after 3 min plasma treatment • Analysis of phenolic compounds of wheat radicles and coleoptiles 23 h after germination by reversed phase HPLC revealed the presence of at least 5 species each, which showed an altered pattern after 10 min of plasma treatment • Total phenolic content was unaltered in wheat coleoptiles and reduced in radicle after 10 in plasma treatment • In oat coleoptiles, total phenolic content including vitexin was decreased after 10 min plasma treatment and decrease in radicles was more pronounced	[305]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae rice *Oryza sativa* L. variety Shoniaush	DBD at 4.5 kHz and 5 kV P: 10 Torr FG: Ar/ Air Power: 45 W TT: 2, 4, 6, 8, 10 min	• SEM analysis revealed smoothening of the seed surface with increasing plasma TT • All TTs resulted in higher germination percentage recorded at day 3 of germination • Biomass parameters (shoot and root length, dry weight) and chlorophyll content of 8 days old seedlings were significantly accelerated for all TTs • Soluble protein contents in leaves were significantly higher for all TTs, while no changes in roots were observed • Soluble sugar contents were significantly higher for TTs > 6 min in leaves and for TTs > 8 min in roots • H_2O_2 contents were increased in shoots and roots for TTs > 8 min, while NO levels were unchanged • SOD and APX activities in shoots significantly increased for all TTs, while CAT activities was increased for 2, 6 and 8 min plasma treatments • SOD activity was unchanged in roots and root APX activity was accelerated for 8 and 10 min TTs, while significant increase of CAT activity was observed for TTs > 6 min	[30]
Family: Poaceae wheat *Triticum aestivum* L. variety Darya			
Family: Poaceae maize *Zea mays* L. hybrid Nemo 216 SV	RF at 5.28 MHz P: 40–80 Pa FG: air Power density: 0.34–0.65 W cm^{-3} TT: 2–10 min	• SEM analysis revealed smoothening of wheat and lupine surface structure after 5 min plasma treatment at 66.5 Pa and 0.34 W cm^3 • Seed viability for wheat and maize treated with plasma or vacuum were improved compared to untreated seeds • Seed viability for lupine seeds treated for 10 min with plasma was lowered and all other treatment parameters were unchanged • Shoot lengths of wheat and maize seedlings tended to increase while shoot lengths of lupine seedlings tended to decrease after plasma or vacuum treatment	[83]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Fabaceae narrow-leaf lupine *Lupinus angustifolius* L. Variety Pershatsvet			
Family: Poaceae wheat *Triticum* spp. L.	RF at 3×10^9 MHz P: 150 Pa FG: He Power: 60, 80, 100 W TT: 15 s	• Germination percentage at day 3 and 7 significantly higher for 80 W plasma treated seeds, while germination of 60 and 100 W plasma treated seed was unaffected • Field experiments performed with 80 W plasma treated seeds revealed significant higher biomass parameters (shoot and root lengths and fresh weight) of seedlings 70 days after seeding • Biomass parameters (plant height, root length, fresh weight, stem diameter, leaf area and leaf thickness) of growing plants together with chlorophyll and nitrogen content at boot stage (approx. 5 months after seeding) were increased as well • Yield (t ha^{-1}) of plasma treated wheat was increased by 5.89% more than that of the control	[139]
Family: Poaceae wheat *Triticum aestivum* L.		• Germination of wheat was accelerated for applied powers up to 160 W	
Family: Poaceae maize *Zea mays* L.	RF at 13.56 MHz P: 30–200 Pa FG: air and air/He mixture Power: 60–180 W TT: 5 - 90 s	• Plasma treatment improved germination parameters (germinability, germination percentage) of aged seeds from wheat, maize and pumpkin • Field experiments revealed a slight increase in wheat grain number, thousand grain weight and ears per plant for different plasma treatments (60, 100, 140 W)	[381]
Family: Cucurbitaceae pumpkin *Cucurbita* L.		• Field experiments with 160 W plasma treated pepper seeds revealed increased plant height and higher shoot branch number	
Family: Solanaceae pepper *Capsicum annuum* L.			

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae wheat *Triticum aestivum* L. cv. BARI Gom 22	DBD at 4.5 kHz and 5 kV P: 10 Torr FG: Ar/O_2 and Ar/air mixture Power: 45 W TT: 90 s	• SEM analysis revealed rougher and chapped seed surface for both plasma treatments • Plasma treatment improved viability of germination without changing median germination time • Shoot biomass parameters of seedlings increased (length, dry weight) while root biomass parameters were decreased • H_2O_2 content in seeds, shoots and roots of seedlings significantly increased • CAT activity significantly accelerated in seeds while SOD and APX activity were unchanged • Plasma treatment of seeds did not lead to membrane damage or cell death in roots and shoots of seedlings • SOD activity and mRNA abundance in roots and APX activities in shoots significantly increased for Ar/O_2 plasma treated seeds, while enzyme activities (CAT, SOD and APX) and mRNA abundance of enzymes were unchanged in the respective organs and treatment modes • Iron content significantly increased in roots while zinc content was dramatically decreased • Total sugar contents in shoots significantly increased	[276]
Family: Poaceae wheat *Triticum aestivum* L. cv. BARI GOM 28	Glow discharge at 3–5 kHz P: 10 Torr FG: air and air/O_2 mixture Power: 60 W TT: 3, 6, 9, 12, 15 min	• WU increased with TT for both FGs applied • Germination parameters (rate, index, vigor, viability, median germination time) positively affected for all TTs and FGs applied • Shoot dry weight of 20 days old plants accelerated for all plasma treatment parameters applied • Increase in chlorophyll content more pronounced for air/O_2 mixture at all TTs • Plants from 3 and 6 min plasma treated seeds displayed higher grain weight and yield	[285]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Poaceae wheat *Triticum aestivum* L. cv. Shannong 12	RF at unknown frequency P: 130–160 Pa FG: air/He mixture Power: 80 and 100 W TT: 15 s	• Wheat seed germination and field growth improved for three different generations of seeds • Values of seed germination parameters (rate, potential, index) and values of biomass parameters of seedlings (seedling shoot lengths, root lengths and number of lateral roots) increased after plasma treatment • Field experiments showed that plasma treated seeds displayed better field growth performance resulting in improved tillering, biomass production and finally yield	[123]
Family: Polygonaceae common buckwheat *Fagopyrum esculentum* Moench cv. VB Vokiai cv. VB Nojai	RF at 5.28 MHz P: 200 Pa FG: air Power density: 0.025 W cm^{-3} TT: 5 and 7 min	• Maximum germination and median germination time was not altered in cv. VB Vokiai after plasma treatment, but median germination time was significantly improved for cv. VB Nojai • Field trials revealed a reduced seedling emergence (11–20%) of plasma treated seeds at day 6 after sowing • Biomass parameters (plant height, dry weight, root and leaf weight, leaf number and lateral branches) of 4 weeks old plants from cv. VB Vokiai were significantly improved for 7 min plasma treated seeds • Positive effects on biomass parameters were less pronounced for cv. VB Nojai after 4 weeks of growth but significantly improved after 8 weeks of growth including weight of generative organs and number of shoots per plant • Photosynthetic activity was much more enhanced in cv. VB Nojai • Yield (seed weight, number of seeds per plant) was significantly increased for both cultivars and both TTs • Total phenolic contents were decreased, and the flavonoid quercetin contents were increased in the harvested seeds from plasma treated cv. VB Vokiai plants	[131]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Solanaceae bell pepper *Capsicum annuum* L. cv. California wonder	Glow discharge at 500 V and 0.2 A P: 0.2 mbar FG: O_2 Power: 100 W TT: 3, 6, 9, 12, 15 min	• SEM analysis revealed etching of seed surface after plasma treatment at undefined TT • WCA was reduced after plasma treatment at undefined TT • Positive effects on germination parameters (germination percentage, speed) and seedling vigor were observed for all TTs • Positive effects on germination parameters were still detectable after 12 months of seed storage • In combination with osmopriming after plasma treatment, all germination and seedling parameters were further increased even after storage of up to 12 months	[234]
Family: Solanaceae tomato *Solanum lycopersicum* L. cv. Shanghai 906	RF at 13.56 MHz P: 150 Pa FG: He Power: 60, 80, 100 W TT: 15 s	• Germination percentage at 3 and at 7 days of germination was significantly improved for 80 W plasma treated seeds • 36 days old plants of 80 W plasma treated seeds displayed significant biomass parameters (total dry weight, leaf area, root length and dry weight, root surface area and volume) • Nitrogen and phosphorous content in plants 80 W plasma treated seeds were significantly increased • Germination and plants' biomass parameters, nitrogen and phosphorous contents of 60 and 100 W treated seeds displayed a positive but not significant trends	[142]

(continued)

Table 6.5 (continued)

Plant species	Plasma parameters	Observed effects	References
Family: Solanaceae tomato (*Solanum lycopersicum* L.)	RF at 13.56 MHz P: 150 Pa FG: He Power: 80 W TT: 15 s	• Positive effect on germination potential and germination rate • Long-term effects of plasma treatment on biomass, stress and antioxidant related enzymes and pathogen infection were observed • Increased biomass parameters (plant length, leaf thickness, stem diameter, dry weight) of plants grown for 30 days in pots • Plasma treatment resulted in increased levels of H_2O_2 and increased activities of POD, PPO and PAL in leaves • Disease development of plants inoculated with the bacterial wilt pathogen *Ralstonia solanacearum* reduced after plasma treatment	[140]

RF—radio frequency; P—pressure; FG—feed gas; TT—treatment time; WCA—water contact angle; WU—water uptake; SOD—superoxide dismutase; APX—ascorbate peroxidase; CAT—catalase; POD—peroxidase; PPO—polyphenol oxidase; PAL—phenylalanine ammonia lyase

287]), and lentil (e.g. [34]) belong to staple food, while alfalfa [80], blue lupine or clover (e.g. [211]) are used for feed production and are relevant in crop rotation because of the symbiotic activity with nitrogen-fixing bacteria. Increase in seed germination after plasma treatment has been also detected for seeds from rapeseed (e.g. [178, 270]) or sunflower (e.g. [203, 371]) known as oil plants. Moreover, this also applies for seeds from vegetables (e.g. radish [202]); spinach [136, 310]; tomato [196], zucchini [151], spices (e.g. pepper, [325, 341]), herbs (e.g. coriander, [135]; sweet basil [7, 317]), pharmaceutical relevant plants (e.g. ginseng, [174]); ajwain, [92]; hemp, [306]; safflower, [69] or trees (e.g. empress tree, [269, 389]); Norway spruce [258] and black pine [309].

6.3.1 Plasma Effects on Seed Surface Morphology

Depending on the plasma intensity of direct plasma treatment mode, outer seed surfaces can be modified leading to cracks, holes and fissures caused by etching and erosion events. Optical analysis by Scanning Electron Microscopy (SEM) is frequently applied to detect changes on seed surfaces by atmospheric DBD or low-pressure RF plasma treatment.

Several studies using DBDs documented surface modifications of wheat seeds after non-thermal plasma treatment [99] detected cracks on seed surface after 4 min air plasma treatment. [207] showed etching effects on the seed coat, which occurred after the air, nitrogen and argon plasma treatments, causing the change in hygroscopicity and permeability of the wheat seed. Li et al. [179] observed gradual destruction of square mesh structures and occurrence of cracks with elevated treatment time of air plasma. Molina et al. [220] found that the seed pericarp was progressively etched and damaged with increasing helium plasma exposure. Changes started with random nano-grooves on the outer layer at treatment times of 5 min, which extended when the treatment time was further increased to 15 min.

Moreover, other plant species were subjected to DBD treatment like barley, pea, thale cress or quinoa [256] investigated barley seeds and reported that plasma treated seed surface were etched and eroded after nitrogen/air plasma treatment for 40 s. Pea seeds were used by Gao et al. [89] displaying distorted and partially destroyed surfaces and ridges on the seed epidermis which gradually dissolved caused by seed coat erosion via bombardment of seeds with free radicals and ions of air plasma treatment at 15 W for 3 min. In addition [330], applied air DBD treatment to pea seeds and observed an uneven disruption, abrasion or even loosening of original structures in testal areas near the plumule- and radicle apex, especially after 10 min exposure. Effects of plasma on the model plant thale cress has been studied as well [54] presented dose-dependent etching effects of air plasma on seed surface encompassing slight shrinkages at 1 min treatment time up to detached epidermis at 10 min plasma exposure. Similarly, Bafoil et al. [16, 18] found changes on the seed surface after air plasma treatment for 15 min. The authors observed a physicochemical etching of

the surface by plasma treatment due to rearrangement of macromolecular structures and exudation of lipid compounds from the seed.

In further studies, no damage (e.g. cracks, holes) of seed surface structure was observed after plasma treatment using a DBD plasma sources, e.g. pea [334], radish [159], spinach [136], sweet basil [7], maize [380], onion [340] or wheat [190].

Low-pressure plasma is also able to modify seed structure (Table 6.5). Flax seeds experienced etching of the cuticle and an accompanied weakening of the underlying mucilage secretory cell (MSC) walls [61]. Although longer RF plasma treatments (15–20 min) induced extensive cracking of the outer integument, the water uptake was not affected [281]. reported a rougher seed surface and an increasing amount of material being removed at 20 Pa with elevated treatment times, which resulted from energetic ions that impinge on the surface. On safflower seeds treated with low-pressure argon RF plasma for 130 min, changes in seed structure and a smoothening relative to the untreated control seeds appeared [69]. Quinoa seeds displayed plasma etching affecting the pericarp after non-thermal plasma treatment [96].

In general, observed modifications of seed surfaces after plasma treatment can be related to following factors: particle bombardment of highly energized species, local heat generation and possibly the individual nature with respect to heterogeneous morphological structures and chemical compositions of outer seed layers. Overall, there are critical methodological aspects for the visual detection of these changes by SEM: 1. SEM analysis provides only a spatially limited section of the entire seed surface. 2. Most seed surfaces are not homogeneous but are highly structured, requiring extensive surface analysis. 3. Eventually, a great number of single SEM pictures have to be analyzed, in addition to different individual seeds to conclude generalizations. 4. SEM analysis of seeds is performed in high or low vacuum and hence plasma effects on seed surfaces could be intensified.

6.3.2 Chemical Modification of the Seed Surface

During direct plasma treatment, bombarded by exited particles such as radicals and ions that can lead to erosion, etching and even chemical modification of the seed surface. This changes the chemical structure and morphology of the surface (e.g., roughness). Interaction of electrons and ions with outer surface layers result in modification and finally higher wettability [34]. Chemical modifications provoked by treatments using gaseous plasma that contain certain proportion of oxygen have been detected in several studies in which oxidation of seed surfaces irrespective of plant origin was observed (e.g. wheat, barley quinoa; [38, 96, 219, 220, 240, 325]) (see also Tables 6.4 and 6.5). Three different methods have been applied to study potential chemical modification: (1) X-ray photoemission spectroscopy (XPS), (2) attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (ATR-FTIR) and (3) Time of Flight-Secondary Ion Mass Spectrometry (ToF-SIMS). Mainly XPS has been applied to detect chemical changes, because this method can detect elements and their chemical state (e.g. oxidation and binding energy) located at seed surfaces,

such as carbon, nitrogen, oxygen, potassium, sodium, magnesium and calcium (e.g. [96, 99, 116, 281, 325]). A correlation between relative oxygen abundance and plasma exposure times from 10 s up to 15 min were noticed on wheat seed surfaces [220]. The increased carbon-oxygen bonds were attributed to air impurities of the DBD device operated using helium at 5 slm. [380] analyzed maize seed surfaces using ATR-FTIR after exposure to DBD treatment for 60 s and found an increased occurrence of polar nitrogen and oxygen containing groups. RONS generated by DBD led to oxidation of lipids located at pea seed surface and subsequent increase in water uptake performance of peas [334]. The decrease of C-H bonds, typical for fatty acids, was more pronounced when air or oxygen was used as feeding gas. However, it was not stated if band intensity typical for oxygen containing groups were increased in FTIR spectra. Bormashenko et al. [34] analyzed the surfaces of wheat and lentil seeds treated with low-pressure air RF plasma using ToF-SIMS and found that a higher proportion of O-containing groups and N-containing groups could be detected on seed surfaces.

6.3.3 Alterations of Seed Surface Hydrophobicity

Physicochemical alterations of seed surfaces can result in changes of surface hydrophobicity. Wettability of seed surfaces can be estimated by measuring the water contact angle (WCA) of a tiny water droplet placed onto the surface. Depending on the contact angle, surfaces are referred as hydrophilic (<90°) or hydrophobic (>90°) [87, 168]. The WCA of plant seed surfaces are usually above 90° but can range from 130° to 76° depending on plant species [315]. Increased wettability of seed surfaces are observed after direct plasma exposure in e.g. wheat [34, 71, 190], soybean [175, 264], rapeseed [178], maize [380], lentil [34, 357], bean [34, 281] or barley [38]. Atmospheric pressure plasmas (e.g. DBD, plasma jets) and RF low-pressure plasmas either operating with air [18, 35, 59, 92, 371], oxygen[234, 281], (Piza et al. 2018), nitrogen[115, 119] or with nobles gases argon [38, 49] or helium [5, 175, 177, 219] displayed effects on seed surface wettability. By using a DCSBD system, different applied feed gases (air, oxygen and nitrogen) resulted in similar strong decreases of WCA values of maize seed surface with increasing plasma treatment times from 30 s to 5 min [115]. Comparable changes in surface wettability of wheat seeds by plasma have been reported for various DBD systems working with feed gases air [71, 190, 347], argon [38, 240] or helium [220].

Indirect plasma treatment does not lead to any significant changes in wettability of seed surfaces from wheat [190], Thuringian mallow [259] and rapeseed, barley or lupine [355].

6.3.4 Alterations of Seed Water Absorbance

The seed coat consists of several layers of dead cells. Seeds from several kinds of plant species such as legumes contain a cuticle as the outer layer that is enriched with phenolic compounds and fatty acid derivates resulting in a hydrophobic seed surface. Naturally occurring cracks on seed surfaces of soybean (*Glycine max* (L.) Merr.) can contribute to water uptake during imbibition [194]). Surfaces of caryopses from wheat or barley contain carbohydrate polymers (e.g., cellulose, hemicelluse) and lignin, which renders the surfaces to hydrophobic state. The mandatory initial step for germination is the uptake of water (imbibition process) to enable physiological processes [244]. Uptake of water does not occur evenly along the seed surface area. In seed science, several methods exist to deduce the route of water entry to the inner parts of the seeds, e.g., using dyes or stable isotopes as tracer. Furthermore, prior to imbibition tests, seed structures can be blocked by water impermeable material or dyes and thus can be used to trace the influx of water [65, 186, 385]. Bafoil et al. [17] measured seed permeability of thale cress by absorbance of tetrazolium red. This test is based on the enzymatic oxidization of tetrazolium red by dehydrogenases in the respiratory chain. Interestingly, the permeability was decreased by plasma treatment which seems to be contradictory to most of published research upon seeds.

Soybean seeds exposed to different gaseous plasma such as DBD displayed increased water absorption after one hour of imbibition [335]. The observed alterations were correlated with treatment time from 30 to 120 s and were more pronounced for nitrogen containing plasma compared to air and oxygen plasma. Similar observation using the same experimental setup was found for one hour imbibed pea seeds treated for 60, 180 and 300 s [334]. Wheat seeds with higher water uptake after plasma treatment simultaneously displayed a decrease in weight due to plasma etching process proved by SEM analysis [220]. Interestingly, water uptake of spinach or wheat seeds was unaffected after plasma treatment even though strong decrease in seed surface hydrophobicity was observed [138, 190].

Future research on plasma treatment of seeds should consider analysis of seeds by nuclear magnetic resonance (NMR) or magnetic resonance imaging (MRI). These techniques give more detailed information about water imbibition process as distribution of water under real time conditions can be monitored [33, 128, 263]. These techniques could provide a better understanding of the plasma-induced effects on whole-seed water permeability.

6.3.5 Plasma Effects on Seed Germination and Plant Growth Parameters

It is assumed that enhanced wettability due to physicochemical seed surface modifications is one of the major factors improving seed germination performance. The stimulating effects on seed germination is frequently discussed with the ability of

plasma to break physical dormancy by reducing seed coat hardness and increased water permeability (e.g., [6, 54, 59, 304]). Plasma treated seeds from e.g. artichoke [119], cumin [280], lentil [34], mimosa [59], water melon [191], mung bean [287], pea [330], rapeseed [176], rice [45, 287], wheat [285, 379], or quinoa [96] had a higher water uptake accompanied with faster germination (see also Tables 6.4 and 6.5).

Analysis of germination kinetics to evaluate the effects of plasma on germination performance essentially involves visual monitoring of germination during different time points. The counting of germinated seeds is based on the macroscopic visible emergence of the radicle protruding from the seed [28, 163]. In studies, 1–2 mm minimal radicle length of germinating wheat and barley, [38, 189], half of the length of germinating soybean [175] or approximately 5 mm radicle length of germinating rice and sunflower [150, 322] were defined for germination. The germination value of a defined time point is presented as germination percentage or (cumulative germination percentage) and often referred as 'germination rate' or 'germination potential' in literature. Germination potential and germination rate of control and RF plasma treated wheat seeds were determined at day 3 and at day 7 of germination, respectively [139]. The values for germination rate were slightly higher compared to the germination potential values. Here, 80 W plasma treatment influenced both germination values significantly positive in comparison to unaffected 60 and 100 W plasma treatment. On the other hand, soybean germination potential after 3 days and germination rate after 7 days of control and plasma treated seeds did not vary from each other [175]. This indicate that final germination was almost reached after 3 days of germination and plasma treatment had no effect on the final germination of soybean. Treatment of black gram seeds for 120 s with air DBD plasma under low-pressure improved germination rate recorded at day 3 of up to 10% [31]. Moreover, observation time points and intervals vary among studies. The intervals of observation times can range from hours to several days and observation can last up to 3 weeks or longer. The final germination value and the speed to reach maximum germination depends on several plant related factors such as dormancy state and age of seeds along with plant origin and studied cultivar or variety. Soybean [175] or wheat [38] displayed maximum germination within 3 days with $\geq$80%, irrespective of plasma treatment. In other studies, variation in germination times and maximum germination values can be observed for the same plant species [192, 335], which can be attributed to different applied varieties, cultivars and/or to germination conditions. Molina et al. [220] analyzed wheat germination after plasma treatment using different water supply with 3, 6, and 12 ml. Interestingly, even the longest exposure time of 15 min did not impair seed germination, and seeds from all plasma treatment times displayed the similar maximum germination close to 100% compared to controls after three days. However, plasma treatment times below 2 min resulted in higher germination percentage after 20 and 24 h with 6 and 12 ml water supply. Maximum germination can be affected positively by plasma as shown for e.g., wheat, mimosa or mulungo (Tables 6.4 and 6.5). da Silva et al. [59] found a remarkable increase of final germination for mimosa from 6% for untreated seeds and 50% after 3 min air DBD treatment. Helium DBD treated mulungu seeds had 5% higher maximum

germination after 25 days [6]. An increase of more than 10% in final germination recorded after 10 days was observed in wheat after treatment with air DBD plasma for 20 and 30 s [379]. The maximum germination of hemp seeds treated for 5 min with RF air plasma under low pressure was 20% higher compared to untreated seeds [131].

Time-resolved observation of seed germination include several observation times until final germination value is reached, allows more detailed assumptions about velocity and homogeneity of germination. The kinetics of germination can be described with a sigmoidal or logistic function since the rate of germination is not homogeneous over time. The Richard function [105, 283] has been applied to describe plasma effects on maximum germination, median germination time, uniformity and synchrony of germination in hemp [131], lamb's quarter [304], mimosa [59], mulungu [6], rapeseed [176], red clover [130], soybean [175], sunflower [209] and wheat [276, 285].

Next to monitoring of seed germination via observation at several distinct time points, biomass production such as root and shoot fresh and dry weight, lengths of shoot and roots or total seedling lengths are frequently recorded to deduce the effects of plasma. Furthermore, from those parameters different indices can be calculated such as seedling vigour index, and seedling length index (e.g., [309, 330, 335, 379]).

Seedling growth was monitored for thale cress [160], radish [159, 291, 293], sunflower [336, 390], wheat [207], and sweet basil [7]. Soybean seeds were treated with ceramic DBD fed with argon using different voltages and incubation times, and optimum germination was observed in the treatment with 22.1 kV for 12 s [382]. Germination was also higher for up to 1 min treatment and decreased when seeds were treated longer than 2 min [382]. Biomass parameters (shoot and root weight and length) were positively affected in the treatments from 12 s to 1 min and decreased when seeds were treated longer for 2 min [382]. Besides observable positive effects, extensive exposure of seeds to plasma can lead to inhibitory effects on germination and seedling development (Tables 6.4 and 6.5, e.g., [136, 188, 306, 373]). These can be attributed to high levels of radicals and reactive species within plasma such as ozone or nitric oxides (NO_x), next to heat and/or high electrical fields leading to deep entrance of electrons to the inner parts of the seeds.

6.3.6 Plasma Effects on Seed and Plant Physiology

Despite the fact that plasma treatment can accelerate germination speed, the simplest explanation for the frequently observed enhancement in seedling growth would be that plasma treated seeds exhibit a time advantage and therefore, higher biomasses of seedling shoots and roots is achieved. However, this would result in similar level of shoot and root growth compared to untreated plants, and thus, shoot/root ratios (or root/shoot ratios) would not be altered. A clear shift of growth to either shoot or root could be monitored for e.g. tomato seedlings [196] and wheat [305, 347]. Moreover, view studies noted alterations of root morphology [123, 142, 178, 196, 280]. The

observed alterations on seedling development can be attributed to further effects of plasma components which are different from only physicochemical modification of the seed surface with accompanied wettability and improved imbibition. Here, reactive oxygen and/or nitrogen species (RONS) derived from plasma are the most versatile candidates that can trigger physiological modification and thus have impact on seed physiology with related development and growth processes as well as stress responses [124, 126].

Reactive oxygen species are known to play pivotal role during plant life cycle and are involved in many responses to biotic and abiotic stress factors [121]. During several steps of germination process reactive oxygen species are formed and play a positive role for dormancy release [244]. Externally applied hydrogen peroxide can stimulate pea seed germination with different effects on phytohormone levels of ABA, auxin, SA, JA and cytokinins [24]. In general, primary metabolism, growth and development related as well as stress relevant factors are frequently analysed in plasma studies.

Soybean seedlings six days after seed treatment with plasma showed an increase in levels of soluble protein, ATP, superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and adenosine triphosphate (ATP) and a decrease in malondialdehyde (MDA) [382]. Alterations in antioxidant activities in seedlings of plasma treated seeds were found for various plant species and different plasma exposures as well (see Tables 6.4 and 6.5). Expression of chloroplast ATP synthase subunits was accelerated, and methylation level in *ATP a1, ATP b1, TOR, GRF 5,* and *GRF 6* genes decreased [382]. Altogether, the argon plasma used promoted germination and growth by increasing the concentrations of soluble protein and antioxidant enzymes and regulating the demethylation levels of ATP, TOR, and GRF.

Any observed changes in germinating seeds after plasma treatment is likely a result of the time advantage of germination process, which may be associated with a change in levels of phytohormones. Phytohormones such as abscisic acid (ABA) and gibberellins (GA) are involved in regulation of germination initiation and germination process. ABA plays a role in seed dormancy (and stress responses), and gibberellin contributes to the initiation of germination. Two phytohormones, auxin and cytokinin, play a pivotal role during entire life cycle of plants, and ratio(s) of phytohormones is important for seed germination and seedling development. Moreover, these phytohormones are mandatory for development of shoots and roots.

Total cytokinin content increases during the first two days after imbibition in germinating *Tagetes minuta* L. seeds and declined during further seedling growth [326, 327]. Similarly, pea, maize, oat, and alfalfa display species specific dynamics of cytokinin levels during germination process and seedling growth [133, 328]. Comparable to phytohormone changes, levels of amino acids and sugars display different pattern during seedling development and growth [44, 79]. Plasma treated dry seeds showed significant changes in phytohormones content and ratios of gibberellins and ABA as well as auxins and cytokinins [1, 99, 175, 179, 209, 256, 330].

Polyphenols are secondary metabolites and belong to markers for different kinds of stresses such as excessive light, heat, drought, flooding etc. Phenolic contents in upper parts of the plants were assessed in barley [319], shoot and roots of wheat

[305], spinach [136], and pea [40] after plasma treatment. In wheat, levels of some phenols were slightly increased while others were unchanged or even decreased. In barley shoots, 6 min plasma treatment led to a significant increase in level of total phenolic compounds [319]. When barley seeds were indirectly treated by DBD driven air plasma for 6 min, increase in seedling weight and shoot length as well as increased levels in primary and secondary metabolites, like phenols, in leaves were observed [319].

Analysis of plasma effects on seed germination and seedling growth are mostly undertaken under laboratory conditions. However, proof of concept of stimulating effects of plasma on plant performance needs to be evaluated under agricultural relevant cultivation conditions. These include growth in soil and soil-like substrates but also cultivation in greenhouse and on fields are mandatory. Few studies exist so far performing green house or field trials. Field trials were performed with peanut and rape by Li et al. [176, 177], hemp [130], red clover [211], maize and wheat [84], wheat [123, 139] and maize and pepper [381]. Important traits to evaluate the efficiency of plasma treatment are biomass parameters that are correlated to yield which include number of flowers, number of seeds per plant, seed weight and weight of seeds per harvest area.

6.4 Application of Non-thermal Plasma to Food Sanitation

Food sanitation is the most actively explored area in the application of non-thermal plasma in the food industry. The antimicrobial activity of plasma *in vitro* has been demonstrated in numerous studies using food poisoning and spoiling microorganisms in planktonic and biofilm states [290]. Furthermore, experimental data are accumulating on sanitation and inactivation of microorganisms contaminating fresh produce, packaged foods, and processed foods, by plasma [346].

6.4.1 Vegetables and Fruits

Post-harvest fruits and vegetables are most frequently examined for microbiological sanitation using non-thermal plasma. Microbial contamination of fruits and vegetables can originate from pre-harvest infection or contamination during storage. To improve the shelf life and storage period of harvested fruits and vegetables, it is essential to inactivate microorganisms. Non-thermal plasma can efficiently deactivate the inoculated microbes and natural microflora on post-harvest fruits and vegetables, as demonstrated in previous studies (Table 6.6). Therefore, it is considered a potential tool for post-harvest sanitation. In most studies, plasma has been applied to fruits and vegetables after artificial inoculation with microorganisms (Table 6.6). However, there are also studies showing the plasma-mediated deactivation of natural microflora associated with fruits and vegetables [32, 93, 107, 164, 183, 221, 272, 338, 363, 366].

Regardless of whether they were inoculated or naturally contaminated with microorganisms, fruits and vegetables were directly exposed to plasma flame or plasma-generated gas. In relatively few studies, plasma-treated water has used for microbial decontamination [363, 366]. Treatment with dry plasma compared to plasma-treated water may be helpful in preventing the introduction of moisture, which can promote microbial growth. Microbial inactivation by dry plasma or plasma-treated water in post-harvest fruits and vegetables shows a proportional increase in response to the treatment time. Roughly about 0.3–7 log CFU reduction depending on treatment time, plasma sources, and feeding gas was observed in most studies (Table 6.6). The difference in inactivation efficiency between bacteria and fungi was not obvious.

Various non-thermal plasma sources such as plasma jets, DBD plasma, gliding arc plasma, corona discharge plasma, and microwave plasma are used for decontamination (Table 6.6). In most of the studies, plasma was generated mostly under atmospheric pressure. However, a group used plasma generated under low pressure [302]. Fruits and vegetables used to analyze the antimicrobial activity of non-thermal plasma are categorized into three groups: fresh fruits such as grape, banana, lemon, strawberry, blueberry, palm, melon, citrus, cantaloupe, and apple; dry nuts such as almond, hazelnut, and pistachio; and fresh vegetables such as corn salad leaves, lettuce, tomato, carrot, black pepper, red chicory, spinach, perilla, mung bean sprout, and argula leaves (Table 6.6). Additionally, Xu et al. [366] investigated the antimicrobial effects of plasma-treated water on button mushrooms and demonstrated that mushrooms had less microorganisms and could be stored for longer after soaking in the plasma-treated water.

Mycotoxin, a secondary metabolite produced by some fungi, is a food contaminant that threatens human and animal health [201]. Fruits and vegetables infected with mycotoxin-producing fungi have recently become a major concern in food safety [329]. Non-thermal plasma is also used to inactivate toxin-producing fungi and remove mycotoxins. The removal and degradation of mycotoxins by plasma in vitro have already been demonstrated in several studies [113, 253, 339]. Studies have also demonstrated that mycotoxins associated with dry nuts and grains, particularly aflatoxin B1, are efficiently degraded by non-thermal plasma[68, 114, 273, 303]. Additionally, mycotoxin levels have been controlled by inactivating producer fungi on fruits and vegetables using plasma. [248] observed that germination of spores and the levels of aflatoxin B2 and ochratoxin A decreased after date palm fruits inoculated with *Aspergillus niger* were exposed to a plasma jet.

Impact of plasma treatment on the quality of fruits and vegetables as food was analyzed together with antimicrobial activity in most studies (Table 6.6). This analysis is very important to determine whether plasma doses sufficient to kill microorganisms negatively affect the quality of fruits and vegetables as food. The most frequently analyzed quality factors are color, flavor, pH, and antioxidant activity. Studies have demonstrated that maximal antimicrobial efficiency of plasma does not always result in no damage to the food quality of fruits and vegetables. This indicates that there is an optimal plasma treatment condition (mostly treatment time) that produces efficient antimicrobial activity without significant damage to the quality of fruits and vegetables. It may be necessary to identify a proper point balancing between

Table 6.6 Application of non-thermal plasma to foods

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Food microbial safety			
Fruits and vegetables			
Grape and banana (Natural microflora)	High field plasma (ambient air)	No increase in bacterial and mold load on fruit surface during storage	[183]
Almonds (*Salmonella Escherichia coli* O157:H7)	AC plasma jet (air, N_2)	Maximum 1.34 log CFU reduction	[239]
Corn salad leaves (*E. coli*)	RF plasma jet (Ar)	Maximum 2.1–3.6 log CFU reduction No significant change in quality	[21]
Lettuce, tomato, and carrot (*E. coli*)	plasma (Ar)	Maximum 1.6 log CFU reduction No change in color parameters and cell structure	[27]
Rice and lemon (Natural microflora)	Surface discharge plasma (ambient air)	Inactivation of mold spores	[107]
Cherry tomato, strawberry (*E. coli*, *Salmonella* Typhimurium, *L. monocytogenes*)	DBD plasma (ambient air)	3.1–6.7 log CFU reduction	[388]
Black pepper (*Bacillus subtilis* spores, *B. atrophaeus* spores, *S. enterica*)	RF plasma, microwave plasma (Ar)	2.4–4.1 log CFU reduction	[112]
Blueberry (Natural microflora)	AC plasma jet (air)	0.8–2.0 log CFU/g reduction	[164]
Cabbage, lettuce, and dried figs (*Salmonella* Typhimurium)	Microwave plasma (N_2, He + O_2)	0.3–1.8 log CFU/g reduction	[170]
Date palm fruit(*Aspergillus niger*)	AC plasma jet (Ar)	Decrease in spore viability and the level of aflatoxin B_2 and ochratoxin A	[248]
Maize (*Aspergillus falvus Aspergillus parasiticus*)	Plasma jet (air, N_2)	Maximum 5.20–5.48 log CFU/g reduction	[56]
Romaine lettuce (*E. coli* O157:H7, *Salmonella* isolates, *L. monocytogenes*, Tulane virus)	DC DBD plasma (ambient air)	0.4–1.3 log CFU/g reduction	[213]
Grape, strawberry, and cherry tomato (Natural microflora)	Low frequency powered DBD plasma (air)	Lower survival of yeasts and molds during storage	[221]
Red chicory (*E. coli* O157:H7, *L. monocytogenes*)	DBD plasma (air)	1.35 log MPN/cm^2–2.2 log CFU/cm^2 reduction	[257]
Fresh cut melon (Natural microflora)	DC DBD plasma (air)	Delayed growth of microorganisms Weak effects on melon quality	[338]

(continued)

Table 6.6 (continued)

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Button mushrooms (Natural microflora)	Plasma treated water	Maximum 0.5–1.5 log CFU reduction Delayed softening and no significant change in quality	[366]
Citrus (*Penicillium digitatum*)	DBD plasma (ambient air)	Significant deactivation of spores No significant change in citrus surface	[370]
Grape tomato, spinach, and cantaloupe (*E. coli* 0157:H7, *Salmonella* Typhimurium, *L. innocua*)	Plasma activated H_2O_2 aerosol	1.0– 5.0 log CFU/piece reduction No significant change in quality	[141]
Almonds (*Salmonella* Enteritidis PT30)	DC SBD plasma (air, O_2, N_2, CO_2, CO_2 + Ar)	2.0 → 5.0 log CFU reduction Browning of surface color	[111]
Mandarin (*P. italicum*)	Microwave plasma (N_2, He, N_2 + O_2)	Significant decrease in spore viability by N_2 plasma Increase in total phenolic content and antioxidant activity of mandarin peel	[359]
Berries (Natural microflora)	Microwave plasma (Ar)	Decontamination efficiency depending on surface roughness No significant change in antioxidant activity of berries	[32]
Perilla leaves (*Staphylococcus aureus*, *E. coli*)	AC DBD plasma (air)	1.6–4.8 log CFU/ml reduction	[137]
Almonds (*E. coli*)	Gliding arc plasma (air)	Complete inactivation	[149]
Apple (*Salmonella*, *E. coli*)	Corona discharge plasma (air)	0.6–5.5 log CFU/cm^2 reduction	[152]
Black pepper (*B. subtilis*, *E. coli*, *Salmonella* Enteritidis)	SBD plasma (ambient air)	1.0–6.6 log CFU/g reduction No significant change in surface morphology	[226]
Kumquat fruit(Natural microflora)	Corona discharge plasma jet (ambient air)	0.77–1.57 log CFU/g reduction No significant change in taste, flavor, color, texture	[272]
Fresh cut lettuce and fresh mung bean sprouts (*E. coli*, *Listeria innocua*, *Pseudomonas fluorescens*, *P. marginalis*, *Pectobacterium carotovorum*)	Microwave plasma generated gas (ambient air)	Maximum >5 log CFU/ml reduction	[296]
Paprika (*Fusarium oxysporum*)	Plasma jet (air)	50% inhibition of fungal growth No significant change in color and hardness	[94]
Hazelnut (*A. parasiticus*, *A. flavus*)	Atmospheric pressure plasma jet (air, N_2), low pressure plasma (air, N_2, O_2)	4.7–5.6 log CFU/g reduction	[302]

(continued)

Table 6.6 (continued)

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Mun bean sprouts (Natural microflora)	Plasma activated water	2.32–2.84 log CFU/g reduction No significant change in total phenolic and flavonoid content and sensory characteristics	[363]
Arugula leaves (Natural microflora)	SDBD plasma (ambient air)	0.57–1.02 log CFU reduction No significant change in quality	[93]
Black pepper and Allspice berries Juniper berries (*Bacillus subtilis*, *A. niger*)	Microwave plasma (Ar)	Partial inactivation of *A. niger* and less effective against *B. subtilis*	[358]
Pistachio nuts (*A. flavus*, aflatoxin B_1)	DBD plasma (air)	Maximum 4 log CFU reduction Effects on some qualities	[199]
Citrus (*P. venetum*)	DBD plasma (air)	90% reduction in cell viability	[289]
Mycotoxin removal			
Hazelnuts (aflatoxin)	DBD plasma (O_2, N_2)	Over 70% reduction in total aflatoxin and aflatoxin B_1 concentration	[313]
Groundnuts (aflatoxin)	RF plasma (ambient air)	70–90% reduction in aflatoxin B_1	[68]
Hazelnuts (aflatoxin)	Atmospheric pressure plasma jet (air), low pressure RF plasma (air)	70–71% reduction in aflatoxin B_1	[303]
Rice and wheat (aflatoxin)	Corona discharge plasma jet (ambient air)	45–56% decrease in aflatoxin B_1 concentration	[273]
Corn kernels (aflatoxin B_1)	DC SBD plasma (ambient air)	Complete removal minor effects on quality	[114]
Meats, meat products, and fishes			
Bacon (*L. monocytogenes*, *E. coli*, *Salmonella* Typhimurium)	Glow discharge plasma (He, He + O_2)	2.6–4.58 log CFU/g reduction No significant change in quality	[153]
Chicken breast, ham (*L. monocytogenes*)	Plasma jet (He, N_2, He + O_2, N_2 + O_2)	1.37–6.52 log CFU/g reduction	[172]
Chicken skin and breasts (*L. innocua*)	Plasma (He, O_2)	1–3 log CFU/cm^2 reduction	[245]
Chicken breast and thigh (*S. enterica*, *Campylobacter jejuni*)	DBD plasma (air)	1.25–3.11 log CFU reduction	[70]
Porcine (Natural microflora)	Microwave plasma (air)	10^2–10^3 CFU/g reduction No significant change in color, pH, fluorescence, and reflectance	[88]

(continued)

Table 6.6 (continued)

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Pork loin (*L. monocytogenes*, *E. coli*)	DBD plasma (He + O_2)	0.55–0.59 log CFU/g reduction Significant reductions in sensory quality parameters (appearance, color, odor, acceptability)	[154]
Chicken breast (*E. coli*)	Plasma jet (N_2, O_2)	1.85 log CFU/g reduction	[375]
Beef loin, pork shoulder, and chicken breast (murine norovirus, hepatitis A virus)	Plasma jet (N_2)	90–99% reduction of viral titer	[15]
Pork butt and beef loin (*L. monocytogenes*, *E. coli* O157:H7, *Salmonella* Typhimurium)	Flexible thin-layer DBD plasma (air)	1.90–2.68 log CFU/g reduction Minor deterioration of meat quality	[134]
Filefish fillets (*Cladosporium cladosporioides*, *Penicillium citrinum*)	Cold oxygen plasma (O_2; BioZone Scientific International Inc.)	0.91–1.04 log CFU/g reduction No significant deleterious change in physicochemical and sensory qualities	[255]
Pork (Natural microflora)	Pulsed plasma (He, Ar, N_2)	2.7–3.08 log CFU/cm^2 reduction No significant change in color and pH	[345]
Pork slices (*L. monocytogenes*, *E. coli* O157:H7)	Corona discharge plasma jet (air)	1.0– 1.5 log CFU reduction No significant changes in oxidation and sensory qualities Changes in color and appearance	[48]
Chicken breasts (*L. monocytogenes*, *E. coli* O157:H7, *Salmonella* Typhimurium)	Flexible thin-layer DBD plasma (air)	2.14–3.36 log CFU/g reduction Minor changes in sensory properties	[171]
Eggs (*Salmonella* Enteritidis)	Plasma jet (Ar, Ar + O_2; kINPen 09®)	0.22–2.27 log CFU reduction	[225]
Smoked salmon (*L. monocytogenes*, *L. innocua*, *Salmonella* Typhimurium, *Salmonella* Enteritidis, *S. aureus*, *E. coli* O157:H7, *Aeromonas hydrophila*, *Plesiomonas shigelloides*)	Plasma (air)	0.1–1.57 log CFU reduction Minor effects on quality	[50]
Ham (*Salmonella* Typhimurium, *L. monocytogenes*)	Plasma (ambient air)	Maximum 1.02–1.14 log CFU reduction	[182]
Sliced pastirma (*S. aureus*, *L. monocytogenes*)	Plasma (Ar, O_2)	4.88–4.93 log CFU/cm^2 reduction Decrease in moisture content	[95]

(continued)

Table 6.6 (continued)

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Ham (*L. innocua*)	DBD plasma (ambient air)	1.43–1.78 log CFU/cm^2 reduction Some changes in quality	[368]
Oysters (Human norovirus)	Micro DBD plasma (N_2)	Over 90% reduction in copy number with propidium monoazide pre-treatment No significant change in quality	[47]
Salmon sashimi (Human norovirus)	Plasma jet (air, O_2, N_2)	About 20–100% reduction in copy number No significant change in quality	[122]
Chicken drumsticks (Natural microflora)	Plasma activated lactic acid	Maximum >1 log CFU/g reduction and increase in storage time No significant change in color components and decrease in MDA content Improvement of aggregation of myofibrillar proteins	[275]
In-package foods			
Pork butt and beef loin (*Listeria monocytogenes*, *E. coli* O157:H7, *S. typhimurium*)	DBD plasma (O_2 and N_2)	1.90–2.68 log CFU reduction Minor deterioration in meat quality	[134]
Broiler breast fillets (Natural microflora)	DBD plasma (ambient air)	1.53–5.53 log CFU/ml reduction	[162]
Pistachio (*A. flavus*)	DBD plasma (ambient air)	Spore deactivation	[318]
Chicken breast fillets (Natural microflora)	DBD plasma (ambient air, $O_2 + CO_2 + N_2$)	Significant reduction in viability under $O_2 + CO_2 + N_2$ Negative effects on chicken meat appearance	[353]
Beef jerky (*E. coli* O157:H7, *L. monocytogenes*, *Salmonella* Typhimurium, *A. flavus*)	Flexible thin-layer DBD plasma (ambient air)	2–3 log CFU/g reduction Slight changes in the physicochemical quality	[377]
Herring fillets (Natural microflora)	DBD plasma (air)	Significant reduction in microbial load Maintain key quality factors at low voltage	[3]
Chicken breast meat(*Campylobacter jejuni*, *Salmonella* Typhimurium)	AC DBD plasma (air)	>90% reduction in microbial CFU Paler meat color	[386]
Chicken breasts (*Salmonella* Enteritidis, *S.* Montevideo, *S.* Typhimurium, Tulane virus)	DBD plasma (air)	0.7–1.7 log CFU/cube reduction No change in pH, color, volatile nitrogen, lipid oxidation, tenderness, sensory qualities	[169]

(continued)

Table 6.6 (continued)

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Ham (*L. monocytogenes*)	DBD plasma ($O_2 + CO_2 + N_2$, $CO_2 + N_2$, CO_2)	>2 log CFU/cm^2 reduction Significant changes in lipid peroxidation and color	[369]
Processed foods			
Brown cereal bars (*A. flavus*)	RF plasma jet (Ar)	Inhibition of fungal growth for up to 20 days	[332]
Red pepper powder (*A. flavus*, *B. cereus*)	Microwave plasma (N_2 and O_2, He and O_2)	1–2.5 log CFU/g reduction for *A. flavus* 3.4 log CFU/g reduction in the combination with heat treatment for *B. cereus*	[155]
Sliced cheese (*E. coli* 0157:H7, *Salmonella* Typhimurium, *L. monocytogenes*)	DBD plasma (ambient air) flexible thin-layer DBD plasma (ambient air)	1.65–3.10 decimal CFU reduction 2.1–5.8 log CFU/g reduction Effects on cheese quality	[374, 376]
Wheat flour (Natural microflora)	DC plasma (ambient air)	No change in bacterial and fungal counts Modification of flour functionality	[20]
Insect flour ((Natural microflora)	SDBD plasma (air)	4.73–7.1 log CFU/g reduction Effects on quality	[41]
Onion powder (*B. cereus*, *A. brasiliensis*, *E. coli* O157:H7)	Microwave plasma (He)	1.6–2.1 log CFU/cm^2 reduction No significant change in quality	[156]
Orange juice (*S. enterica*)	DBD plasma (ambient air, $O_2 + CO_2 + N_2$)	2.2 → 5 log CFU reduction Effects on quality	[365]
Saffron (Naturally contaminated fungi)	Low pressure RF plasma (O_2)	Eradication of fungi at 60 W and 15 min treatment Minor effects on quality	[118]
Apple juice (*E. coli*)	DBD plasma (ambient air)	3.98–4.34 log CFU/ml reduction Mino effects on quality	[181]
Apple juice (*Zygosaccharomyces rouxii*)	Surface discharge plasma (air)	6.58–6.82 log CFU reduction	[354]
Kimchi cabbage (Natural microflora)	Plasma activated water	0.9–2.2 log CFU/g reduction	[46]
Orange juice (*Penicillium expansum*, *P. buchwaldii*, *P. bialowiezense*)	Plasma jet (N_2)	1–3 log CFU reduction	[97]
Coconut water (*Salmonella* Typhimurium)	DBD plasma (air)	1.30–5 log CFU reduction Minor effects on quality	[195]

(continued)

Table 6.6 (continued)

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Tiger nut milk (Natural microflora)	DBD plasma (air)	>4 log CFU/ml reduction Changes in quality	[231]
Tomato juice (Natural microflora, *Candida albicans*, *Saccharomyces cerevisiae*)	AC gliding arc plasma (N_2)	>3 log CFU/ml reduction Minor effects on quality	[323]
Cheese (*L. innocua*, *E. coli* K12)	DBD plasma (ambient air, $O_2 + CO_2 + N_2$)	1.6–5.0 log CFU/g reduction 1.4–3.5 log CFU/g reduction Minor effects on quality	[350, 351]
Powdered Spirulina algae (*B. subtilis*)	SMD plasma (air, N_2)	2 log CFU reduction Some changes in quality	[29]
Tomato juice (Natural microflora)	Gliding arc plasma (N_2)	3 → 5 log CFU/g reduction No significant change in quality	[324]
Mixed nuts snack	Plasma (ambient air)	Significant decrease in microbial load Significant increase in the peroxide level and ΔE index	[19]
Rice germ, black pepper powder, and sesame (Natural microflora)	Plasma jet (air)	– 1.4 log CFU/g reduction No change in quality	[173]
Kiwi turbid juice (Natural microflora)	DBD plasma (ambient air)	83.97% bactericidal effect Minor effects on quality	[184]
Milk (Natural microflora)	Low pressure DBD plasma (ambient air)	~95% reduction of coliform microbes	[200]
House cricket powder (Natural microflora)	SMD plasma (ambient air)	1.6–1.9 log CFU reduction No significant change in quality	[268]
Food quality and functional property			
Lamb's lettuce	Plasma jet (Ar)	Changes in phenolic profile	[98]
Fructooligosaccharides (food ingredient)	Plasma (ambient air)	No significant change in quality during food processing	[85]
Alkaline phosphatase (native enzyme in milk)	DBD plasma (ambient air)	Inactivation of enzyme Change in secondary protein structure	[300]
Soybean oil	AC DBD plasma (H_2, $H_2 + N_2$)	Partially hydrogenated soybean oil without the formation of trans-fatty acids	[372]

(continued)

Table 6.6 (continued)

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Cut apple and potato	Microwave plasma (ambient air)	62–89% reduction in polyphenol oxidase and peroxidase activities to inhibit undesirable browning	[39]
Meat batter	DBD plasma ($N_2 + O_2$)	Addition of nitrite into meat	[144]
Peanut oil	AC plasma (Ar)	No deterioration of quality Increase in storage period	[282]
Inulin	DBD plasma(air)	Depolymerization of inulin to fructose Production of fructooligosaccharides	[236]
Lemon verbena	Low pressure microwave plasma (N_2, Ar, O_2)	0.9–1.2% reduction in essential oil content Increase in the content of monoterpene hydrocarbons and oxygenated sesquiterpenes	[75]
Peanut	SDBD plasma (air)	Decrease in unsaturated fatty acid and moisture content Increase in saturated fatty acids, peroxide value, acid value, and total polyphenols	[90]
White grapes	Plasma jet (air)	Faster drying and formation of raisins Improvement of quality	[120]
Tomato-based beverage	DBD plasma (air)	Retaining and improving the content of ascorbic acid, chlorogenic acid, sinapic acid and gallic acid	[206]
Corn starch	Plasma jet (air)	Increase in solubility and paste clarity of starch	[361]
Pork jerky	DBD plasma (ambient air)	Increase in redness, nitrosoheme pigment content, and residual nitrite content Decrease in microbial load	[378]
Maize starch	Plasma jet (air)	Modification of starch properties	[384]
Grape pomace	AC DBD plasma (He)	10.9–22.8% increase in yield of phenolic extracts Improved nutritional quality	[23]
Wheat flour	DBD plasma (ambient air)	Increase in hydration, pasting, viscosity of flour Depolymerization of starch	[43]
Fenugreek	DBD plasma (air)	67–122% increase in galactomannan extraction	[279]

(continued)

Table 6.6 (continued)

Target foods (microorganisms)	Plasma types (feeding gas)	Effects	References
Pearl millet	Plasma (air)	Improvement of hydration and pasting properties	[185]
Flaxseed extracts	Plasma jet (air)	Tailoring techno-functionality of extracts	[237]
Fresh cut endive	Plasma treated water	Improvement of color and texture properties	[295]
Starch	RF or DBD plasma (Ar)	Increase in the ordering and stability of starch molecules by modifying amylose chains	[314]
Wheat gliadin	AC plasma jet (He)	Modification of physiochemical and functional properties	[333]
Soybean protein isolate	DBD plasma (ambient air)	Improved functionality and reduced allergenicity	[383]

antimicrobial activity and food quality control, even though complete microbial decontamination cannot be achieved.

6.4.2 Meats, Meat Products, and Fishes

Despite their high nutritional value as a protein source, meat, meat products, and fish can be easily contaminated with microorganisms, causing food poisoning and other foodborne diseases [62]. Non-thermal plasma has been used for the decontamination of meat and meat products such as chicken, pork, beef, ham, bacon, and eggs (Table 6.6). Recently, seafood such as fish filets, oysters, and salmon sashimi have been actively explored in plasma applications [47, 122, 255]. In many studies, the antimicrobial activity of plasma was assessed on microbes inoculated onto meats and fish. Several studies have focused on the contamination of natural microflora [88, 275, 345]. Among microorganisms, food poisoning bacteria such as *E. coli, L. monocytogenes, Salmonella* spp., and *Campylobacter jejuni* were more frequently targeted than fungi (Table 6.6). Park et al. [255] inoculated the *P. citrinum* fungus on filefish filets and decontaminated it with oxygen plasma. Norovirus was also targeted for plasma-mediated decontamination. Norovirus is a pathogenic virus that causes vomiting and acute gastroenteritis; consumption of contaminated foods is one of the routes for disease outbreaks [284]. Several studies have shown the efficient decontamination of beef, pork, chicken, oysters, and salmon sashimi contaminated with norovirus of human or murine origin by plasma [15, 47, 122]. As observed in the decontamination of fruits and vegetables, plasma flame or plasma-generated gas generated from various plasma sources was more frequently applied to meats, meat products, and fish than plasma-treated water or liquids (Table 6.6). Interestingly, Qian et al. [275] found that plasma-activated lactic acid was more effective in decreasing microbial load contaminated on chicken drumsticks than plasma-treated water.

Generally, non-thermal plasma treatment, either gaseous plasma or plasma-treated liquid, can deactivate bacteria inoculated or contaminated on meats, meat products, and fish, with an efficiency of 0.1–6.52 log CFU reduction depending on treatment time and conditions. Regarding viruses, over 90% of murine norovirus and hepatitis A virus copy numbers were reduced after plasma treatment of contaminated beef, pork, and chicken [15]. In oysters contaminated with human norovirus, the virucidal effect of plasma was negligible (<1 log copy number/μL) without propidium monoazide pre-treatment and greater (>1 log copy number/μL) with propidium monoazide pre-treatment [47]. Huang et al. [122] found that N_2 plasma deactivated the human norovirus in salmon sashimi with an efficiency of 20% reduction in copy number, and the level of norovirus was undetectable after treatment with O_2 plasma.

No or minor deterioration in food quality, such as lipid peroxidation, pH, and sensory properties (appearance, color, odor, acceptability), was observed in the majority of studies (Table 6.6). However, Kim et al. [154] demonstrated that sensory

quality parameters such as appearance, color, odor, and acceptability were significantly reduced after plasma treatment of bacteria-contaminated pork loin. This indicates that condition tuning or the development of methods for quality control may be necessary for industrial and market applications.

6.4.3 Packaged Foods

Various food products and fresh produce are often distributed as packaged materials in the market and industry. Prevention of microbial contamination during the packaging process can play an important role in ensuring a long shelf life. Thermal treatment is a routine method for sanitation of packaged foods. However, deterioration of food quality has limited the range of applications of thermal sanitation. Fresh produce is more frequently distributed in packaged states in recent markets. The demand for non-thermal sanitation technologies has increased, particularly in the management of packaged foods.

Non-thermal plasma has demonstrated the potential for microbial decontamination of packaged foods over the last decade. A distinguishing point in these studies was that foods were treated with plasma generated inside the package. Recently, Misra et al. [215] reported an excellent review of the application of non-thermal plasma technology to the sanitation of packaged foods. In Table 6.6, studies excluding those mentioned in Misra et al.'s review are indicated. Various designs of plasma systems specialized for in-package treatment have been developed; a package is placed between two electrodes, electrodes are placed on one side of the package, and electrodes are placed inside the package [215]. In most studies, dielectric barrier discharge (DBD) or surface dielectric barrier discharge (SDBD) plasma was used in the treatment of packaged foods (Table 6.2) [215]. Foods inoculated with food poisoning and spoiling bacteria are most frequently targeted for in-package plasma treatment [215], whereas fungi and viruses have rarely been explored [169, 213, 318, 377]. Foods contaminated with natural microflora were also analyzed after in-package plasma treatment [3, 4, 162, 189, 204, 214, 353, 387]. The efficiency of in-package food sanitation using plasma is good; a >1 log reduction in CFU number has been observed in most studies, and complete eradication of microorganisms has been demonstrated in some cases [4, 103, 172, 387, 388].

In-package food quality after plasma treatment is also an important factor to be considered. Most studies have demonstrated that in-package plasma treatment causes minor or no changes in physiological, physical, and sensory properties (Table 6.6) [215]. However, a recent study demonstrated that plasma treatment could result in lipid peroxidation and significant color changes in packaged ham [369].

6.4.4 *Processed Foods*

Plasma has been actively applied to the sanitation of processed foods such as juice, milk, cheese, pepper powder, insect powder, and snacks (Table 6.6). Non-thermal tools such as ultrasonification, UV, ionizing radiation, and electrical fields have been applied to the sanitation of heat-sensitive foods [274]. Non-thermal plasma is also considered a promising technology that can efficiently remove microbial contamination during food processing and packaging. Liquid foods such as fruit juice and milk have been frequent targets for plasma sanitation, and a greater than 1 log reduction in bacterial CFU number was obtained after plasma treatment (Table 6.6). In various studies, the quality of juices and milk was not significantly affected by plasma (Table 6.6). However, Xu et al. [365] found that direct treatment with 90 kV high voltage atmospheric cold plasma reduced vitamin C content by 22% and pectin methylesterase activity by 74–82% in orange juice. Muhammad et al. [231] showed that DBD air plasma caused a significant reduction in pH, protein content, and peroxidase activity in tiger nut milk, whereas no significant changes in soluble solids and fat contents were observed.

The sanitation of dry foods and powders using plasma resulted in an efficient >1 log reduction in CFUs in most cases (Table 6.6). Bacteria inoculated on sliced cheese were efficiently inactivated in encapsulated or flexible thin-layer DBD plasma systems, and some food qualities such as flavor, overall acceptance, and off-color were significantly affected by plasma [374, 376]. Dry powders, such as onion powder, black pepper powder, and insect powder, were efficiently decontaminated with no dramatic changes in food quality [156, 173, 268]. Several studies have demonstrated that plasma treatment can alter protein solubility and the amount of lipids, chlorophyll a, carotenoids, phycobilin, and total phenolic compounds in wheat flour, insect powder, and algae powder [20, 29, 41]. Particularly, Bahrami et al. [20] observed no significant changes in total aerobic bacterial count or total mould count in wheat flour after treatment with 0.19 and 0.43 W/cm^2 air plasma.

6.5 Application of Non-thermal Plasma to Food Quality and Functional Property

Non-thermal plasma has also been used to enhance the quality and functionality of foods and food ingredients (Table 6.6). The quality and nutritional value of fresh produce are investigated together during plasma sanitation to determine whether plasma treatment can affect food quality. Color, texture, pH, proteins, carbohydrates, vitamins, lipids, and antioxidant activity are major properties frequently analyzed in previous studies [249]. These factors are mostly related to the taste, nutritional value, and senescence of the fresh produce. In many studies, plasma treatment did not cause significant damage to the quality of fresh produce. Improvement in antioxidant activity and increase in phenolic content are often observed in lettuce, cut apples,

potatoes, peanuts, and grapes [23, 39, 90, 98]. Rinsing with plasma-treated water can improve the color and texture of fresh-cut endives [295]. Plasma can also increase the speed of drying and improve the quality of raisins from fresh grapes [120].

Furthermore, studies have demonstrated that plasma can affect the quality and functionality of food ingredients and processed food products (Table 6.6). The redness of meat can be improved by increasing the amount of nitrite in the meat after plasma treatment [144, 378]. The nutritional value of several herbs, such as fenugreek, pearl millet, and lemon verbena, is also enhanced by plasma. Plasma can facilitate the acquisition of galactomannan from fenugreek, improve the hydration of pearl millet, and elevate the contents of monoterpene hydrocarbons and oxygenated sesquiterpenes in lemon verbena [75, 185, 279]. Moreover, starch structure can be modified by plasma, which can further alter the properties of starch such as solubility, depolymerization, and paste viscosity, making it more suitable for food and non-food industries [43, 314, 361, 384]. Plasma can improve the storage of soybean and peanut oils and the functionality of wheat and soybean proteins [333, 383]. Additionally, plasma can increase depolymerization of inulin for the production of fructooligosaccharides without changing its quality as a food ingredient [85, 236].

6.6 Conclusion and Future Perspectives

Non-thermal atmospheric- and low-pressure plasma are promising tools for several applications, such as microbial decontamination and activation of seed germination and growth, in the food and agriculture industries. However, the mechanisms underlying plasma action, standardization of applied plasma dose, and development of industrial-scale treatments still need for intense further study. The scale addressed in the agriculture and food industries is relatively large compared to that in the medical field, and this should be considered when developing a plasma system. Another future direction in plasma application may be that plasma can be explored to find a potential solution to agricultural and food issues resulted from climatic change. Due to climate change, the current agriculture and food industry is facing a big challenge, and improvement in stress tolerance and storage of fresh produce has received increasing attention as emerging areas wherein plasma can be applied.

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