Non-Thermal Plasma for Microbial Decontamination and Chemical Removal

Subjects: Green & Sustainable Science & Technology

Contributor: Yovana Todorova, Evgenia Benova

Plasma is a quasi-neutral system in a gaseous or fluid-like form that can be artificially generated in an electromagnetic field and a flow of neutral gases such as helium, argon, nitrogen, oxygen, or atmospheric air. It contains a mixture of radicals, H2O2, O3, ultraviolet radiation, charged particles, exited metastable atoms, and electric fields. Non-thermal atmospheric plasma has recently attracted great research interest as an alternative for operative solutions to problems related to safety and quality control. It is a powerful tool for the inactivation of different hazardous microorganisms and viruses, and the effective decontamination of surfaces and liquids has been demonstrated. Additionally, the plasma's active components are strong oxidizers and their synergetic effect can lead to the degradation of toxic chemical compounds such as phenols and azo-dyes.

Keywords: non-thermal atmospheric plasma ; microbial decontamination ; chemical removal ; safety

1. Introduction

Our contemporary society is facing many environmental challenges due to the unprecedented level of industrialization, urbanization, and exponential growth of the human population. The increasing generation and disposal of wastes, environmental pollution, source depletion, biodiversity loss, climate changes, and growing energy demand are global threats to our sustainable development and require a fundamentally new rethinking to reduce the consumer footprint on nature [1][2][3][4]. The transformation of our linear "take-make-waste" system to the cyclic flow of materials and energy is urgent, and this is a key driver for the rapid development and promotion of the circular economy concept. The circular economy has the potential to overcome challenges by following three general principles: "(1) preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows; (2) optimize resource yields by circulating products, components, and materials in use at the highest utility; (3) foster system effectiveness by revealing and designing out negative externalities" [5][6]. The most widely applicable aspects of the circular economy include eco-design for sustainability, an extension of the product life cycle, and implementation of "reduce, reuse and recycle" option in waste management [7][8]. However, the closing of loops in different industrial sectors by circulation, reuse, and recycling of materials and products brings to the fore other key issues—those related to safety and the prevention of risks from secondary contamination. Ensuring a high level of uncompromising safety in circular economy practices is a priority task and an important keystone for the achievement of high social acceptance and positive user perceptions and attitudes.

When discussing safety issues, it must be taken into account that safety includes both microbiological and chemical aspects. The context of the circular economy is no exception-we must be sure that the use of waste streams from one industry/sector as a material input for another is completely safe and the possibility for the crossover of chemical or microbiological hazards is eliminated/minimized. The problem is escalating nowadays with the enormous production and use of chemicals, resulting in a global scale of chemical pollution, and the pandemic distribution of unknown viruses and multidrug-resistant bacteria [9][10]. It is clear that we urgently need new advanced approaches ensuring both microbiological safety and the removal of potential chemical residues in different materials and products, with the quick achievement of the high safety level, easy operation, lack of residual toxicity, and wide use with no application restrictions [11][12][13]. Facing these scientific and practical challenges, it seems that one well-known physical phenomenon—plasma—and some recently developed plasma-based technologies can effectively respond to these requirements.

Plasma is a quasi-neutral system in a gaseous or fluid-like form that can be artificially generated in an electromagnetic field and a flow of neutral gases such as helium, argon, nitrogen, oxygen, or atmospheric air. It contains a mixture of radicals, H_2O_2, O_3, ultraviolet radiation, charged particles, exited metastable atoms, and electric fields [14][15]. The plasma active components individually are well-known sterilization agents, and as expected, their combination in plasma has a strong synergistic effect and provides high bactericidal efficiency with low costs, timesaving, and non-toxicity.

Based on the temperature of particles, there are two types of plasmas: high-temperature plasmas (fusion plasmas) and low-temperature plasmas (non-thermal or cold plasmas) [14]. Each type of plasma has a specific application and benefits but in the field of biosafety and microbiological control of different materials and products, the leading role of non-thermal plasma is undoubted, especially the type generated at atmospheric pressure [11][15][16][17][18][19][20][21][22][23][24][25][26][27]. Its main advantage is a simple and less expensive plasma source operating in an open space without thermal damage to treated materials. Non-thermal plasmas may be generated by direct current (DC) discharge, radio frequency discharge, dielectric barrier discharge, pulsed power, and surface wave (microwave) discharge. Microwave plasma is not in equilibrium, the electron energy distribution function is non-Maxwellian, and the temperature of the heavy particles is much lower than the electron temperature [28]. Non-equilibrium, non-thermal atmospheric pressure plasma (also called cold atmospheric plasma—CAP) is suitable to treat living tissues, heat-sensitive materials, foods, and bio-compatible materials, and has wide use in medicine, the agro-food industry, and microbiological control. The use of CAP is not limited to alternative sterilization or therapeutic technique for biomedical application—the plasma-based approach has an important role in the solution of some critical environmental issues. Recent data show its significant potential as an effective tool in pollution control and the treatment of different polluted sources. Looking at the wide field of plasma applications from a different perspective, it is clear that this huge potential can successfully contribute to improving the microbiological and chemical safety of products and materials in the circular economy.

2. Low-Temperature Non-Equilibrium Plasma for Microbial Decontamination

For convenience, the specific fields of CAP where its germicidal effect is used can be generalized as follows: (1) plasma-aided medical therapies, (2) plasma-assisted dentistry, and (3) plasma-based decontamination and sterilization for microbiological control in agriculture, food industry, microbiology, water treatment, etc.

The interaction of CAP with living objects, bacteria, spores, and viruses has been extensively studied in the last decades, and basic principles have been defined [29][30][31][32]. The main attention has been paid to plasma's killing effect on bacteria (both Gram-positive and Gram-negative), bacterial spores, biofilms, and fungi. A significant efficiency of treatment has been gained with different CAP-generated configurations against a large number of pathogens with high-risk profiles: *Escherichia coli*, *Listeria monocytogenes*, *Salmonella enterica*, *Staphylococcus sp*., *Pseudomonas aeruginosa*, *Bacillus sp*.; and spores such as *Candida albicans* [33][34][35][36][37][38][39][40]. The bactericidal effect of CAP is clearly expressed in the treatment of biofilms on different surfaces and bacterial suspensions in liquids. Viruses and prions have been studied to a lesser extent, but in the last two years, this gap has begun to fill intensively due to the COVID-19 crisis [41][42][43]. Many studies have demonstrated the ability of non-thermal plasma to be an effective virucidal agent. The plasma treatment reduces virus burdens on contaminated surfaces and airborne viruses. and can be applied for successful prevention and interference of virus replication [44].

Some of the hypotheses for the inactivation mechanism of CAP on bacteria are summarized by Fernandez and Thompson as follows [45]: the destroying effect of UV irradiation on DNA according to its power density and wavelength range [46]; damage from the diffusion of reactive species through membranes and their reaction with cell macromolecules [47]; the etching effect on the cell surface by direct bombardment with free radicals [48]; erosion of the microorganisms through intrinsic photodesorption by UV [49]. The last two lead to a massive leakage of cell content, a strongly negative effect on cell adhesion at biofilm growth, and the interruption or inhibition of biofilm quorum sensing systems [50].

In the field of agriculture and food processing, the search for new promising and effective "cleaning" tools with a multipurpose application based on cold atmospheric plasma has also been the subject of many types of research [16][24][51][52][53][54][55]. The growing need for "green", un- or less processed food with high quality, safety, and preserved taste and nutrients leads to a very attractive rating of CAP as a powerful non-thermal sterilization technique. The recent studies are aimed at the treatment of food products, food processing devices, packaging materials, functionality modification of food materials, and removal of agrochemical residues [22][56][57][58]. Non-thermal atmospheric plasma is a promising decontamination technology for the inactivation of bacteria, yeasts, molds, and fungal and bacterial spores both on the foods and on the abiotic surfaces of packages or processing equipment [59]. The obtained results reveal promising opportunities to use CAP to ensure safety, especially in the case of the entry of waste streams in different stages of processing. The reuse of composted food wastes or activated sludge as fertilizer in agriculture, for example, may increase microbiological risk, while appropriate plasma treatment of the final product may eliminate the hazard. Additionally, plasma can be used for alternative food processing to obtain the desired color of meat products without adding chemicals, to improve the extraction of essential oils, or to extend the life of some products [27][59].

3. Low-Temperature, Non-Equilibrium Plasma for Removal of Hazardous Chemicals

The growing production, wide use, and subsequent discharge of different toxic and persistent pollutants in the environment are another serious threat to human and ecosystem health. The effective solution of associated environmental problems needs adequate pollution control based on innovative approaches, and plasma technologies are one of the promising new alternatives. Considerable attention of researchers has been focused on plasma-assisted removal of volatile organic compounds from polluted air, and significant results have already been achieved in this area [60][61][62][63]. In the last years, these technologies have been applied for the treatment of gases from animal production to food processing facilities, and a high removal and energy efficiency has been achieved [64]. Solid waste and soil treatment is another area of research interest where the focus is mainly on thermal plasma application, but some types of non-thermal plasmas have been used [65][66]. The efforts in the environmental field of plasma application are related to another target component—water—and its treatment for the removal of organic pollutants. The strong oxidation features of some highly energetic plasma components mean that plasma can be used successfully for the removal of unacceptable organic compounds in wastewater [67][68][69][70][71]. In many advanced strategies for pollution control and management, plasma technologies are considered as one of the options for the substitution of expensive traditional chemical methods in water treatment and the elimination of secondary pollution in treated water. High efficiency has already been achieved in the removal of phenol and a wide range of phenolic derivates [68][71][72][73][74], azo-dyes [65], pharmaceutical and antibiotic compounds [75][76][77], and carbon from plastic waste [78]. Several configurations have been developed and applied for the removal of different organic pollutants during discharge in the gas, liquid, or hybrid liquid-gas phase, such as pulsed high-voltage electrical discharge, glow discharge, and gliding arc [71].

References

1. Ramos, A.; Rouboa, A. Life cycle thinking of plasma gasification as a waste-to-energy tool: Review on environmental, economic and social aspects. Renew. Sustain. Energy Rev. 2022, 153, 111762.
2. Tian, H.; Wang, X.; Tong, Y.W. Chapter 9—Sustainability assessment: Focusing on different technologies recovering energy from waste. In Waste-to-Energy, 1st ed.; Ren, J., Ed.; Academic Press: Amsterdam, The Netherlands, 2020; pp. 235–264.
3. Leading the way to a global circular economy—Publications Office of the EU. Available online: https://op.europa.eu/en/publication-detail/-/publication/31079d7e-3a96-11eb-b27b-01aa75ed71a1 (accessed on 31 January 2022).
4. Hamam, M.; Chinnici, G.; Di Vita, G.; Pappalardo, G.; Pecorino, B.; Maesano, G.; D'Amico, M. Circular Economy Models in Agro-Food Systems: A Review. Sustainability 2021, 13, 3453.
5. Velenturf, A.P.M.; Purnell, P. Principles for a sustainable circular economy. Sustain. Prod. Consum. 2021, 27, 1437–1457.
6. Growth within: A circular economy vision for a competitive Europe McKinsey. Available online: https://www.mckinsey.com/business-functions/sustainability/our-insights/growth-within-a-circular-economy-vision-for-a-competitive-europe (accessed on 31 January 2022).
7. van Dam, K.; Simeone, L.; Keskin, D.; Baldassarre, B.; Niero, M.; Morelli, N. Circular Economy in Industrial Design Research: A Review. Sustainability 2020, 12, 10279.
8. Geueke, B.; Groh, K.; Muncke, J. Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials. J. Clean Prod. 2018, 193, 491–505.
9. Liu, N.; Xu, L.; Han, L.; Huang, G.; Ciric, L. Microbiological safety and antibiotic resistance risks at a sustainable farm under large-scale open-air composting and composting toilet systems. J. Hazard. Mater. 2021, 401, 123391.
10. Azam, S.M.R.; Ma, H.; Xu, B.; Devi, S.; Siddique, M.A.B.; Stanley, S.L.; Bhandari, B.; Zhu, J. Efficacy of ultrasound treatment in the removal of pesticide residues from fresh vegetables: A review. Trends Food Sci. Technol. 2020, 97, 417–432.
11. Zhou, R.; Rezaeimotlagh, A.; Zhou, R.; Zhang, T.; Wang, P.; Hong, J.; Soltani, B.; Mai-Prochnow, A.; Liao, X.; Ding, T.; et al. In-package plasma: From reactive chemistry to innovative food preservation technologies. Trends Food Sci. Technol. 2022, 120, 59–74.
12. Sharma, S.; Jaiswal, S.; Duffy, B.; Jaiswal, A.K. Advances in emerging technologies for the decontamination of the food contact surfaces. Food Res. Int. 2022, 151, 110865.

13. Murugesan, P.; Evanjalin Monica, V.; Moses, J.A.; Anandharamakrishnan, C. Water decontamination using non-thermal plasma: Concepts, applications, and prospects. J. Environ. Chem. Eng. 2020, 8, 104377.
14. Hippler, R.; Kersten, H.; Schmidt, M.; Schoenbach, K.H. (Eds.) Low Temperature Plasmas: Fundamentals, Technologies and Techniques, 2nd ed.; Wiley-VCH: Berlin, Germany, 2008; p. 945.
15. Marinova, P.; Benova, E.; Todorova, Y.; Topalova, Y.; Yotinov, I.; Atanasova, M.; Krcma, F. Surface-wave-sustained plasma torch for water treatment. J. Phys. Conf. Ser. 2018, 982.
16. Bogdanov, T.; Tsonev, I.; Marinova, P.; Benova, E.; Rusanov, K.; Rusanova, M.; Atanassov, I.; Kozáková, Z.; Krčma, F. Microwave Plasma Torch Generated in Argon for Small Berries Surface Treatment. Appl. Sci. 2018, 8, 1870.
17. Benova, E.; Marinova, P.; Tafradjiiska-Hadjiolova, R.; Sabit, Z.; Bakalov, D.; Valchev, N.; Traikov, L.; Hikov, T.; Tsonev, I.; Bogdanov, T. Characteristics of 2.45 GHz Surface-Wave-Sustained Argon Discharge for Bio-Medical Applications. Appl. Sci. 2022, 12, 969.
18. Choi, E.H.; Uhm, H.S.; Kaushik, N.K. Plasma bioscience and its application to medicine. AAPPS Bull. 2021, 31, 10.
19. Patinglag, L.; Melling, L.M.; Whitehead, K.A.; Sawtell, D.; Iles, A.; Shaw, K.J. Non-thermal plasma-based inactivation of bacteria in water using a microfluidic reactor. Water Res. 2021, 201, 117321.
20. Lin, C.M.; Herianto, S.; Chen, H.L.; Chiu, Y.C.; Hou, C.Y. The application of a novel non-thermal plasma device with double rotary plasma jets for inactivation of Salmonella Enteritidis on shell eggs and its effects on sensory properties. Int. J. Food Microbiol. 2021, 355, 109332.
21. Pankaj, S.K.; Bueno-Ferrer, C.; Misra, N.N.; Milosavljević, V.; O'Donnell, C.P.; Bourke, P.; Keener, K.M.; Cullen, P.J. Applications of cold plasma technology in food packaging. Trends Food Sci. Technol. 2014, 35, 5–17.
22. Pankaj, S.K.; Keener, K.M. Cold plasma: Background, applications and current trends. Curr. Opin. Food Sci. 2017, 16, 49–52.
23. Attri, P.; Yusupov, M.; Park, J.H.; Lingamdinne, L.P.; Koduru, J.R.; Shiratani, M.; Choi, E.H.; Bogaerts, A. Mechanism and comparison of needle-type non-thermal direct and indirect atmospheric pressure plasma jets on the degradation of dyes. Sci. Rep. 2016, 6, 1–14.
24. Attri, P.; Ishikawa, K.; Okumura, T.; Koga, K.; Shiratani, M. Plasma Agriculture from Laboratory to Farm: A Review. Processes 2020, 8, 1002.
25. Sarangapani, C.; Patange, A.; Bourke, P.; Keener, K.; Cullen, P.J. Recent Advances in the Application of Cold Plasma Technology in Foods. Annu. Rev. Food Sci. Technol. 2018, 9, 609–629.
26. Thirumdas, R.; Sarangapani, C.; Annapure, U.S. Cold Plasma: A novel Non-Thermal Technology for Food Processing. Food Biophys. 2015, 10, 1–11.
27. López, M.; Calvo, T.; Prieto, M.; Múgica-Vidal, R.; Muro-Fraguas, I.; Alba-Elías, F.; Alvarez-Ordóñez, A. A Review on Non-thermal Atmospheric Plasma for Food Preservation: Mode of Action, Determinants of Effectiveness, and Applications. Front. Microbiol. 2019, 10, 622.
28. Benova, E.; Atanasova, M.; Bogdanov, T.; Marinova, P.; Krčma, F.; Mazankova, V.; Dostal, L. Microwave Plasma Torch at a Water Surface. Plasma Med. 2016, 6, 59–65.
29. Laroussi, M. Low-Temperature Plasmas for Medicine? IEEE Trans. Plasma Sci. 2009, 37, 714–725.
30. Kong, M.G.; Kroesen, G.; Morfill, G.; Nosenko, T.; Shimizu, T.; Van Dijk, J.; Zimmermann, J.L. Plasma medicine: An introductory review. New J. Phys. 2009, 11, 115012.
31. Stoffels, E.; Sakiyama, Y.; Graves, D.B. Cold atmospheric plasma: Charged species and their interactions with cells and tissues. IEEE Trans. Plasma Sci. 2008, 36, 1441–1457.
32. Laroussi, M.; Mendis, D.A.; Rosenberg, M. Plasma Interaction With Microbes. New J. Phys. 2003, 5, 41–42.
33. Klämpfl, T.G.; Isbary, G.; Shimizu, T.; Li, Y.F.; Zimmermann, J.L.; Stolz, W.; Schlegel, J.; Morfill, G.E.; Schmidt, H.U. Cold atmospheric air plasma sterilization against spores and other microorganisms of clinical interest. Appl. Environ. Microbiol. 2012, 78, 5077–5082.
34. Min, S.C.; Roh, S.H.; Niemira, B.A.; Sites, J.E.; Boyd, G.; Lacombe, A. Dielectric barrier discharge atmospheric cold plasma inhibits Escherichia coli O157:H7, Salmonella, Listeria monocytogenes, and Tulane virus in Romaine lettuce. Int. J. Food Microbiol. 2016, 237, 114–120.
35. Modic, M.; McLeod, N.P.; Sutton, J.M.; Walsh, J.L. Cold atmospheric pressure plasma elimination of clinically important single- and mixed-species biofilms. Int. J. Antimicrob. Agents 2017, 49, 375–378.
36. Takamatsu, T.; Kawate, A.; Uehara, K.; Oshita, T.; Miyahara, H.; Dobrynin, D.; Fridman, G.; Fridman, A.; Okino, A. Bacterial Inactivation in Liquids Using Multi-Gas Plasmas. Plasma Med. 2012, 2, 237–248.

37. Timmons, C.; Pai, K.; Jacob, J.; Zhang, G.; Ma, L.M. Inactivation of Salmonella enterica, Shiga toxin-producing Escherichia coli, and Listeria monocytogenes by a novel surface discharge cold plasma design. Food Control 2018, 84, 455–462.
38. Van Gils, C.A.J.; Hofmann, S.; Boekema, B.K.H.L.; Brandenburg, R.; Bruggeman, P.J. Mechanisms of bacterial inactivation in the liquid phase induced by a remote RF cold atmospheric pressure plasma jet. J. Phys. D Appl. Phys. 2013, 46, 175203.
39. Cui, H.; Bai, M.; Yuan, L.; Surendhiran, D.; Lin, L. Sequential effect of phages and cold nitrogen plasma against Escherichia coli O157:H7 biofilms on different vegetables. Int. J. Food Microbiol. 2018, 268, 1–9.
40. Niveditha, A.; Pandiselvam, R.; Prasath, V.A.; Singh, S.K.; Gul, K.; Kothakota, A. Application of cold plasma and ozone technology for decontamination of Escherichia coli in foods—A review. Food Control 2021, 130, 108338.
41. Filipić, A.; Gutierrez-Aguirre, I.; Primc, G.; Mozetič, M.; Dobnik, D. Cold Plasma, a New Hope in the Field of Virus Inactivation. Trends Biotechnol. 2020, 38, 1278–1291.
42. Domonkos, M.; Tichá, P.; Trejbal, J.; Demo, P. Applications of Cold Atmospheric Pressure Plasma Technology in Medicine, Agriculture and Food Industry. Appl. Sci. 2021, 11, 4809.
43. Chen, Z.; Garcia, G.; Arumugaswami, V.; Wirz, R.E. Cold atmospheric plasma for SARS-CoV-2 inactivation. Phys. Fluids 2020, 32, 111702.
44. Mohamed, H.; Nayak, G.; Rendine, N.; Wigdahl, B.; Krebs, F.C.; Bruggeman, P.J.; Miller, V. Non-Thermal Plasma as a Novel Strategy for Treating or Preventing Viral Infection and Associated Disease. Front. Phys. 2021, 9, 683118.
45. Fernández, A.; Thompson, A. The inactivation of Salmonella by cold atmospheric plasma treatment. Food Res. Int. 2012, 45, 678–684.
46. Laroussi, M. Low Temperature Plasma-Based Sterilization: Overview and State-of-the-Art. Plasma Process. Polym. 2005, 2, 391–400.
47. Dobrynin, D.; Fridman, G.; Friedman, G.; Fridman, A. Physical and biological mechanisms of direct plasma interaction with living tissue. New J. Phys. 2009, 11, 115020.
48. Gallagher, M.J.; Vaze, N.; Gangoli, S.; Vasilets, V.N.; Gutsol, A.F.; Milovanova, T.N.; Anandan, S.; Murasko, D.M.; Fridman, A.A. Rapid inactivation of airborne bacteria using atmospheric pressure dielectric barrier grating discharge. IEEE Trans. Plasma Sci. 2007, 35, 1501–1510.
49. Moisan, M.; Barbeau, J.; Moreau, S.; Pelletier, J.; Tabrizian, M.; Yahia, L. Low-temperature sterilization using gas plasmas: A review of the experiments and an analysis of the inactivation mechanisms. Int. J. Pharm. 2001, 226, 1–21.
50. Ziuzina, D.; Boehm, D.; Patil, S.; Cullen, P.J.; Bourke, P. Cold Plasma Inactivation of Bacterial Biofilms and Reduction of Quorum Sensing Regulated Virulence Factors. PLoS ONE 2015, 10, e0138209.
51. Guo, Q.; Sun, D.W.; Cheng, J.H.; Han, Z. Microwave processing techniques and their recent applications in the food industry. Trends Food Sci. Technol. 2017, 67, 236–247.
52. Randeniya, L.K.; De Groot, G.J.J.B. Non-Thermal Plasma Treatment of Agricultural Seeds for Stimulation of Germination, Removal of Surface Contamination and Other Benefits: A Review. Plasma Process. Polym. 2015, 12, 608–623.
53. Ito, M.; Ohta, T.; Hori, M. Plasma agriculture. J. Korean Phys. Soc. 2012, 60, 937–943.
54. Ito, M.; Oh, J.S.; Ohta, T.; Shiratani, M.; Hori, M. Current status and future prospects of agricultural applications using atmospheric-pressure plasma technologies. Plasma Process. Polym. 2018, 15, 1700073.
55. Puač, N.; Gherardi, M.; Shiratani, M. Plasma agriculture: A rapidly emerging field. Plasma Process. Polym. 2018, 15, 1700174.
56. Misra, N.N.; Jo, C. Applications of cold plasma technology for microbiological safety in meat industry. Trends Food Sci. Technol. 2017, 64, 74–86.
57. Chizoba Ekezie, F.G.; Sun, D.W.; Cheng, J.H. A review on recent advances in cold plasma technology for the food industry: Current applications and future trends. Trends Food Sci. Technol. 2017, 69, 46–58.
58. Misra, N.N.; Schlüter, O.; Cullen, P.J.; Patrick, J. Cold Plasma in Food and Agriculture: Fundamentals and Applications; Elsevier: Amsterdam, The Netherlands, 2016; ISBN 9780128014899.
59. Kim, T.-K.; Yong, H.-I.; Jung, S.; Kim, H.-W.; Choi, Y.-S. Technologies for the production of meat products with a low sodium chloride content and improved quality characteristic—A Review. Foods 2021, 10, 957.
60. Dobslaw, D.; Schulz, A.; Helbich, S.; Dobslaw, C.; Engesser, K.H. VOC removal and odor abatement by a low-cost plasma enhanced biotrickling filter process. J. Environ. Chem. Eng. 2017, 5, 5501–5511.

61. Karatum, O.; Deshusses, M.A. A comparative study of dilute VOCs treatment in a non-thermal plasma reactor. Chem. Eng. J. 2016, 294, 308–315.

62. Talebizadeh, P.; Babaie, M.; Brown, R.; Rahimzadeh, H.; Ristovski, Z.; Arai, M. The role of non-thermal plasma technique in NOx treatment: A review. Renew. Sustain. Energy Rev. 2014, 40, 886–901.

63. Vandenbroucke, A.M.; Morent, R.; De Geyter, N.; Leys, C. Non-thermal plasmas for non-catalytic and catalytic VOC abatement. J. Hazard. Mater. 2011, 195, 30–54.

64. Schiavon, M.; Torretta, V.; Casazza, A.; Ragazzi, M. Non-thermal Plasma as an Innovative Option for the Abatement of Volatile Organic Compounds: A Review. Water Air Soil Pollut. 2017, 228, 1–20.

65. Zhang, H.; Ma, D.; Qiu, R.; Tang, Y.; Du, C. Non-thermal plasma technology for organic contaminated soil remediation: A review. Chem. Eng. J. 2017, 313, 157–170.

66. Ho, G.S.; Faizal, H.M.; Ani, F.N. Microwave induced plasma for solid fuels and waste processing: A review on affecting factors and performance criteria. Waste Manag. 2017, 69, 423–430.

67. Du, C.M.; Shi, T.H.; Sun, Y.W.; Zhuang, X.F. Decolorization of Acid Orange 7 solution by gas–liquid gliding arc discharge plasma. J. Hazard. Mater. 2008, 154, 1192–1197.

68. Grabowski, L.R.; Van Veldhuizen, E.M.; Pemen, A.J.M.; Rutgers, W.R. Corona Above Water Reactor for Systematic Study of Aqueous Phenol Degradation. Plasma Chem. Plasma Process. 2006, 26, 3–17.

69. Iya-Sou, D.; Laminsi, S.; Cavadias, S.; Ognier, S. Removal of Model Pollutants in Aqueous Solution by Gliding Arc Discharge: Determination of Removal Mechanisms. Part I: Experimental Study. Plasma Chem. Plasma Process. 2009, 33, 97–113.

70. Wang, L.; Jiang, X.; Liu, Y. Degradation of bisphenol A and formation of hydrogen peroxide induced by glow discharge plasma in aqueous solutions. J. Hazard. Mater. 2008, 154, 1106–1114.

71. Zhang, J.; Chen, J.; Li, X.; Zhang, J.; Chen, J.; Li, X. Remove of Phenolic Compounds in Water by Low-Temperature Plasma: A Review of Current Research. J. Water Resour. Prot. 2009, 1, 99–109.

72. Liu, Y.J.; Jiang, X.Z. Phenol degradation by a nonpulsed diaphragm glow discharge in an aqueous solution. Environ. Sci. Technol. 2005, 39, 8512–8517.

73. Yan, J.H.; Du, C.M.; Li, X.D.; Cheron, B.G.; Ni, M.J.; Cen, K.F. Degradation of Phenol in Aqueous Solutions by Gas–Liquid Gliding Arc Discharges. Plasma Chem. Plasma Process. 2006, 26, 31–41.

74. Cheng, H.; Chen, S.; Wu, Y.; Ho, D. Non-thermal plasma technology for degradation of organic compounds in wastewater control: A critical review. J. Environ. Eng. Manag. 2007, 17, 427–433.

75. Magureanu, M.; Piroi, D.; Mandache, N.B.; David, V.; Medvedovici, A.; Bradu, C.; Parvulescu, V.I. Degradation of antibiotics in water by non-thermal plasma treatment. Water Res. 2011, 45, 3407–3416.

76. Magureanu, M.; Mandache, N.B.; Parvulescu, V.I. Degradation of pharmaceutical compounds in water by non-thermal plasma treatment. Water Res. 2015, 81, 124–136.

77. Zhang, T.; Zhou, R.; Wang, P.; Mai-Prochnow, A.; McConchie, R.; Li, W.; Zhou, R.; Thompson, E.W.; Ostrikov, K.K.; Cullen, P.J. Degradation of cefixime antibiotic in water by atmospheric plasma bubbles: Performance, degradation pathways and toxicity evaluation. Chem. Eng. J. 2021, 421, 127730.

78. Sanito, R.C.; Chen, Y.W.; You, S.J.; Yang, H.H.; Hsieh, Y.K.; Wang, Y.F. Hydrogen and Methane Production from Styrofoam Waste Using an Atmospheric-pressure Microwave Plasma Reactor. Aerosol Air Qual. Res. 2020, 20, 2226–2238.