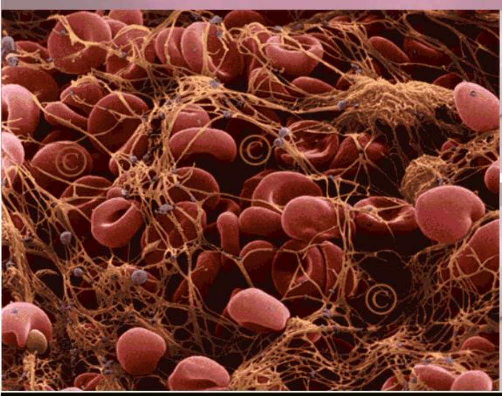
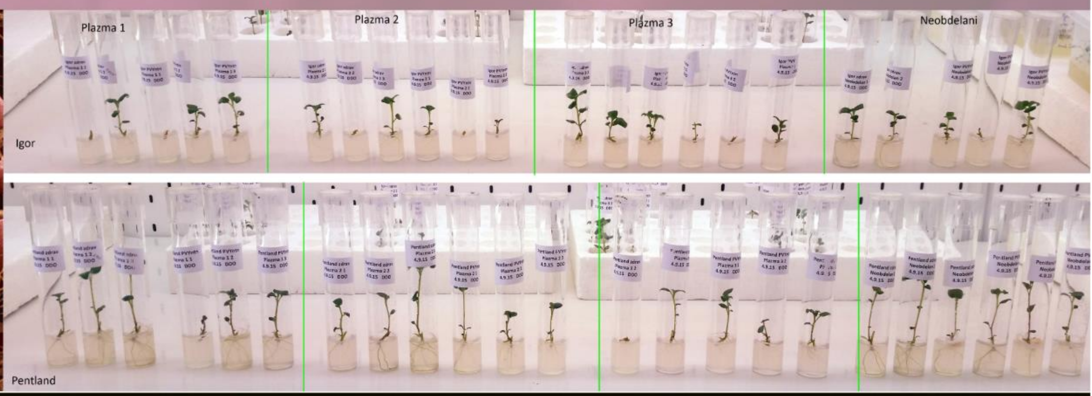
# 8th International Conference on Advanced Plasma Technologies

# 3rd Workshop on Plasma Applications for Smart and Sustainable Agriculture



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Dear Colleagues,

on behalf of the International Scientific Committee and the Organizing Committee, we are pleased to welcome you to Gozd Martuljek (Slovenia) between 16th and 18th May 2023 at the Eighth International Conference on Advanced Plasma Technologies – ICAPT-8. The conference is the first after the virus restrictions, following the previous event in Hue (Vietnam) from 24th February to 1st March 2019. The scope of this conference is gathering renowned scientists and users of plasma technologies. The invited speakers will present recent advances in plasma technologies and stimulate participants to discuss the scientific and technological challenges. Plasma scientists and technologies are facing the transformation of plasma-assisted technologies according to Industry 4.0. The major challenge is pathing the way to smart production lines capable of self-adjusting the plasma parameters according to the prescribed values. Optimizing plasma technologies according to high environmental standards is another challenge, and developing innovative techniques capable of solving crucial issues according to the green transition is perhaps the major challenge for plasma scientists and technologists. All these challenges will be addressed at the conference. Ample time is allocated for formal and informal discussion. The conference is organized just after the annual Workshop of the EU COST Action "CA19110 Plasma applications for smart and sustainable agriculture" between 14th and 16th May 2023. The workshop is a topical meeting specialized in advances in the scientific niche of plasma agriculture, one of the major orientations of future activities in plasma technologies. We wish you all a pleasant stay in Gozd Martuljek.

With best regards, Gregor Primc, Miran Mozetič, and Nevena Puač

Ljubljana, May 2023

# 3rd Workshop on Plasma Applications for Smart and Sustainable Agriculture

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COST Action PlAgri (CA19110) “Plasma Applications for Smart and Sustainable Agriculture”

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

CA19110 Plasma applications for smart and sustainable agriculture

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# 8th International Conference on Advanced Plasma Technologies

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## Program of the 3rd Workshop on Plasma Applications for Smart and Sustainable Agriculture

### Sunday, 14th May

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| **16:30** | **Registration** |
| **18:30** | **Welcome cocktail** |
| **19:00** | **Dinner break** |

### Monday, 15th May

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|---|---|
| **8:30** | **Registration** |
| **8:50** | **Opening of the workshop** |
| | **Session Chairs: Nevena Puač, František Krčma** |
| **9:00** | **Nikola Škoro (Serbia)**; Properties of plasma-treated liquids used in agricultural and water purification applications; **Invited** |
| **9:30** | **Mario Janda (Slovakia)**; Tuning plasma activated water composition generated by transient spark with electrospray; **Invited** |
| **10:00** | **Rasa Žukiene (Lithuania)**; Cold plasma-induced effects in Stevia rebaudiana Bertoni in different experimental models; **Invited** |
| **10:30** | **Coffee break** |
| | **Session chair: Kinga Kutasi** |
| **11:00** | **Dawid Zarzeczny (Poland)**; Influence of low-temperature plasma on the properties of beetroot seeds; **STSM** |
| **11:15** | **Ludmila Čechová (Czech Republic)**; Study of the different plasma sources for water and seed treatment; **STSM** |
| **11:30** | **Piotr Terebun (Poland)**; Impact of plasma activated water prepared by different systems on the selected soil properties; **STSM** |
| **11:45** | **Klaas De Baerdemaeker (Belgium)**; The decontamination of bioaerosols using an in-house rotating dielectric barrier discharge (RDBD) plasma source; **STSM** |
| **12:00** | **Lunch break** |
| | **Session chair: Romolo Laurita** |
| **14:00** | **Clemencia Chaves-López (Italy)**; Antifungal Efficacy of SDBD cold plasma on dried tomatoes and mechanisms of action; **Invited** |
| **14:30** | **James Walsh (UK)**; Perspectives on the in-line decontamination of food-processing surfaces using cold atmospheric pressure air plasma; **Invited** |
| **15:00** | **Fabio Palumbo (Italy)**; Plasma deposition as a possible innovative technology in plasma agriculture; **Invited** |
| **15:30** | **Coffee break** |

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|---|---|
| | **Session chair: Monica Magureanu** |
| **16:00** | **Tom Field (UK)**; A method to control the energy of free electrons in atmospheric pressure plasma discharges; **STSM** |
| **16:15** | **Thomas Vazquez (Slovakia)**; Real scale treatment of indoor air by cold atmospheric plasma and photocatalysis; **Oral** |
| **16:30** | **Mia Ivanov (Croatia)**; Degradability improvement of the olive mill wastewater by high voltage electrical discharge plasma (HVED); **Oral** |
| **16:45** | **Domenico Aceto (Italy)**; The effect of PAW on the growth and gene activation of healthy and tomato-mottle-mosaic-virus inoculated tomato seedlings; **Oral** |
| **17:00** | **Olivera Jovanović (Serbia)**; Argon plasma pin-type jet for water treatment and biological applications; **Oral** |
| **17:15–17:30** | **Zdenko Machala (Slovakia)**; Future agriculture with green fertilizers produced by non-thermal plasma-activated water technology; **Oral** |
| **18:30** | **Dinner break** |
| **20:00** | **PlAgri networking and discussions / Poster session** |

Tuesday, 16th May

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|---|---|
| | Session chair: Zdenko Machala |
| **9:00** | **Tomoyuki Murakami (Japan)**; Numerical simulation and chemical network analysis of plasma-treated water; **Invited** |
| **9:30** | **Anna Dzimitrowicz (Poland)**; Plasma-based technologies for the efficient and economic removal of pharmaceuticals from contaminated water; **Invited** |
| **10:00** | **Vit Jirašek (Czech Republic)**; Direct and imprinted chemical reactivity of plasma-treated solutions; **Invited** |
| **10:30** | **Coffee break** |
| | **Session chair: Joanna Pawlat** |
| **11:00** | **Živko Čurčić (Serbia)**; Plasma in agriculture from agronomist perspective; **Invited** |
| **11:30** | **Liutauras Marcinauskas (Lithuania)**; Extraction of valuable compounds from microalgae using plasma and pulsed electric field treatment; **Oral** |
| **11:45** | **Mark Zver (Slovenia)**; Low-pressure plasma irradiation for water disinfection; **Oral** |
| **12:00** | **Lunch break** |
| | **Session chair: Tomislava Vukušić Pavičić** |
| **14:00** | **Changtao Chen (Belgium)**; Degradation of micropollutants in secondary wastewater effluent using nonthermal plasma-based AOPs; **Oral** |

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|---|---|
| **14:15** | **Paolo Ambrico (Italy)**; On the effectiveness of dielectric barrier discharge treatment against phytopathogenic fungi; **Oral** |
| **14:30** | **Palma Rosa Rotondo (Italy)**; Low-temperature plasma and plasma-activated water as alternative novel technologies for postharvest disease control; **Oral** |
| **14:45** | **Iokeswari Ramireddy (Ireland)**; Influence of cold plasma on agriculture applications of selected multi-species grass sward; **Oral** |
| **15:00** | **Cristina Muja (France)**; Low-pressure microwave air plasma for spices decontamination; **Oral** |
| **15:15** | **František Krčma (Czech Republic)**; The effect of plasma activated water long term application on physical chemical soil properties; **Oral** |
| **15:30** | **Coffee break** |
| | **Session chairs: Nevena Puač/František Krčma** |
| **16:00** | **Alexandra Lavrikova (Slovakia)**; Inactivation of Escherichia coli and Staphylococcus aureus by cold plasma for disinfection of surfaces in food industry; **Oral** |
| **16:15** | **Danyang Liu (Belgium)**; Impact of non-thermal plasma on lipid oxidation: identification of key reactive species; **Oral** |
| **16:30–17:15** | **WG2-WG5 meeting and discussion** |
| **18:30** | **Dinner break** |

## Program of the 8th International Conference on Advanced Plasma Technologies

Wednesday, 17th May

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|---|---|
| **8:30** | **Registration** |
| **8:50** | **Opening** |
| | **Session Chair: Miran Mozetič** |
| **9:00** | **Rajdeep Singh Rawat** (Singapore); Low-temperature plasma processing modulation using external means for electrocatalytic electrode surface manipulation; **Invited** |
| **9:30** | **Kinga Kutasi (Hungary)**; Plasma-assisted modification of colloidal nanoparticles; **Invited** |
| **10:00** | **Jan Hanuš (Czech Republic)**; Plasma-based synthesis of titania nanostructures; **Invited** |
| **10:30** | **Coffee break** |
| **11:15** | **František Lofaj (Slovakia)**; Analysis of reactive sputtering in DC magnetron sputtered and High Target Utilization Sputtered TiNbVTaZrHf-xN coatings; **Invited** |

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| **11:45** | **Tomoyuki Murakami (Japan)**; Integrated numerical modelling of cell fate determination in response to plasma-induced reactive species; **Invited** |
| **12:15** | **Vit Jirašek (Czech Republic)**; Nitrogen fixation in sub-micrometer-size water aerosol using micro-hollow surface DBD reactor; **Invited** |
| **12:45** | **Lunch break** |
| **14:30** | **Tom Field (UK)**; Underwater plasma initiation; **Oral** |
| **14:50** | **Liutauras Marcinauskas (Lithuania)**; Synthesis of molybdenum doped diamond-like carbon films by magnetron sputtering; **Oral** |
| **15:10** | **Changtao Chen (Belgium)**; Degradation of micropollutants in secondary wastewater effluent using nonthermal plasma-based AOPs; **Oral** |
| **15:30–17:00** | **Guided discussion on plasma technologies in industry** |
| **19:00** | **Dinner break** |

## Thursday, 18th May

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|---|---|
| | **Session Chair: Miran Mozetič** |
| **9:00** | **Zdenko Machala (Slovakia)**; Various plasma-liquid discharge regimes determine the plasma-activated water properties and applications; **Invited** |
| **9:30** | **Nikola Škoro (Serbia)**; Regeneration of clinoptilolite saturated with ciprofloxacin by using atmospheric pressure plasma; **Invited** |
| **10:00** | **Mark Zver (Slovenia)**; Waterborne virus inactivation using various low-pressure plasma radiation wavelengths and ambient gases; **Invited** |
| **10:30** | **Zoran Petrović (Slovenia)**; Breakdown and volt-ampere characteristics of low-current discharges in water vapour; **Invited** |
| **11:00** | **Miran Mozetič (Slovenia)**; Plasma technology in industry 4.0; **Invited** |
| **11:30** | **Guided discussions on plasma technologies for the environment** |
| **12:30** | **Conference closing** |
| **12:15** | **Lunch break and departures** |

All contributions are in alphabetical order regarding the first or corresponding author for each section (invited, contribution, oral, poster).

# Plasma in agriculture from agronomist perspective

**Živko Ćurčić, Nada Grahovac, Olivera Popov, Ivana Bajić, Ana Marjanović Jeromela**

Institute of fields and vegetable crops, Novi Sad, Serbia

In recent years, non-thermal plasma (plasma) technology has increasingly been explored in the agricultural field as an ecofriendly alternative to the conventional agrochemical treatments used in pre- and post-harvest (fertilizers, fungicides, plant growth regulators, etc.).

The most prominent widespread plasma applications in agriculture are in these areas: 1. seed processing, 2. greenhouse production and other production under controlled conditions, and 3. post-harvest.

There are a few plasma applications in seed treatment. Seed disinfection with different plasma treatments is used to remove pathogens from the seed surface. These methods can replace different fungicides with contact modes of action. Seed priming with plasma-activated water, enhancing germination percent and accelerating emergence. Application of plasma treatments on powders and binders used for seed pelleting. These treatments also should be focused on promoting emergence and initial growth.

Greenhouse production uses a recirculating nutrient solution that can be contaminated with different microbes. Nutrient solutions are being disinfected with different methods (eat, oxidizing chemicals, UV radiation), which may adversely affect beneficial microorganisms in the recirculated solution. Development of plasma treatments that can save beneficial microorganisms and eliminate pathogens could have a great impact on this type of production.

There are also some reports that indicate plasma could be a prospective control method for fungal pathogens, particularly those that cause post-harvest diseases. Numerous studies have evidenced the effectiveness of plasma sterilization on various foods, such as fresh fruit and vegetables, grains, nuts, spices, and herbs. This technology offers several advantages in terms of operations at room temperature and pressure conditions, dry treatment, short treatment time and, best of all, no residues.

Cold plasma can serve a wide range of applications in the agriculture sector. The only challenge is to figure out whether plasma can be applied at high number of hectares.

# Plasma-based technologies for the efficient and economic removal of pharmaceuticals from contaminated water

**Dominik Terefinko (1), Agata Motyka-Pomagruk (2), Magda Caban (3), Weronika Babinska (2), Piotr Jamroz (1), Piotr Cyganowski (4), Pawel Pohl (1), Wojciech Sledz (2), Ewa Lojkowska (2), and Anna Dzimitrowicz* (1)**

(1) Department of Analytical Chemistry and Chemical Metallurgy, Wroclaw University of Science and Technology, Wroclaw, Poland
(2) Intercollegiate Faculty of Biotechnology University of Gdansk and Medical University of Gdansk, University of Gdansk, Gdansk, Poland
(3) Department of Environmental Analysis, University of Gdansk, Gdansk, Poland
(4) Department of Polymer and Carbonaceous Materials, Wroclaw University of Science and Technology, Wroclaw, Poland

Because endocrine disturbing compounds (EDCs, e.g., bisphenol A, 17-alpha-ethinylestradiol, benzophenone, dapsone, 2-nitrophenol) and antibiotics (e.g. ofloxacin, doxycycline, ampicillin, chloramphenicol) are the most used ones by communities, they easily reach the aqueous environment, leading to its contamination. For this reason, there is a high need to develop versatile procedures for their removal from liquid solutions. Bearing this in mind, in our research group, we have developed, optimized, and applied several continuous flow plasma-based systems, including open-to-air pin-type systems [1,2], helium-atmosphere plasma pencil system [2] and helium-atmosphere plasma brush system [3] for removal of selected drugs from contaminated water. Considering the pin-type system, its applicability for removing EDCs [1] and doxycycline [2] was confirmed. In this case, the removal efficiency of the organic compounds was 79 ± 4.5% for doxycycline [2] and >50% for all of the studied EDCs [1], as was assessed using high-performance liquid chromatography with diode array detection (HPLC-DAD). Taking into account the plasma pencil, its utilization for the removal of studied antibiotics was significantly lower as compared to the plasma brush, i.e. 3-24% versus 29-67%, respectively, as was determined using HPLC-DAD [3]. Performing qualitative and quantitative analyses of Reactive Oxygen and Nitrogen Species (RONS) it was found that removal efficiency depends on the concentration of RONS, especially: ·OH, O, $O_3$, $H_2O_2$, and $HO_2^-$, and a number of plasma cones [3]. By applying ultra-performance liquid chromatography coupled with tandem mass spectrometry (UPLC-MS/MS), the degradation products of studied antibiotics along with decaying pathways were revealed. Additionally, we confirmed that the application of plasma brush for removal of antibiotics from studied solutions led to a decrease of antimicrobial properties up to 81.6%, as was estimated towards Escherichia coli, Bacillus subtilis, Serratia marcescens, and Enterobacter cloacae subsp. cloacae [3]. We truly believe that after scaling up the plasma systems, the utilization of plasma-based technologies will be a tempting alternative for wastewater treatment plants (WWTPs).

Acknowledgements: The studies were financed by National Science Centre (Poland) in the frame of Sonata 15 (UMO-2019/35/D/ST8/04107) research project.

[1] Dzimitrowicz et al., J. Environ. Chem. Eng. 2021, 9, 106718
[2] Dzimitrowicz et al., Sci. Rep. 2022, 12, 7354
[3] Terefinko et al., Chem. Eng. J. 2023, 452,139415

# Tuning plasma-activated water composition generated by transient spark with electrospray

**Mário Janda, Pankaj Pareek, Peter Tóth, and Zdenko Machala**

Faculty of Mathematics, Physics and Informatics, Comenius University, Mlynská Dolina, 842 48 Bratislava, Slovakia

Transient spark (TS) is a DC-driven self-pulsing discharge generating highly reactive atmospheric pressure plasmas. The advantage of TS is its capability of simultaneous generation of the plasma and the formation of microdroplets by the electrospray (ES) of water directly inside the discharge zone. The TS discharge can thus efficiently generate plasma-activated water (PAW) with high concentration of $H_2O^2$(aq), $NO_2^-$(aq) and $NO_3^-$(aq), because water microdroplets significantly increase the plasma-liquid interaction interface.

We studied TS in humid air or $O_2$ feed gas, with and without water ES. We used two experimental setups: a one-stage system where TS and ES can be generated simultaneously and a two-stage system, where the gas was first treated by TS, then sprayed by water ES in the second stage.

In humid air, TS generates high concentrations of NO, HNO2 and NO2, that increased approximately linearly with increasing input energy density (Ed) and reached 1200, 100 and 180 ppm, at $E_d$ = 400 J/L, respectively. In humid $O_2$, TS generates mainly $O_3$ (~40 ppm), with small amount of $H_2O_2$ (~2 ppm) in the gas phase. Thus, TS does not produce significant amount of $H_2O_2$(g) neither in humid air, nor in humid $O_2$. This can explain low concentration of $H_2O_2$(aq) in PAW from the two-stage system (<0.1 mM). High concentration of $H_2O_2$(aq) was measured only in PAW generated with $O_2$ feed gas in the one-stage system (1.2–1.7 mM). Our results indicate that the direct contact of discharge with liquid water is crucial and solvation of short living species, such as OH radicals, probably plays crucial roles in the generation of $H_2O_2$(aq) in PAW. In addition, we proved that gaseous $HNO_2$, rather than NO or $NO_2$, plays a major role in the formation of $NO_2^-$(aq) in PAW.

This work was supported by Slovak Research and Development Agency APVV-17-0382 and Slovak Grant Agency VEGA 1/0596/22 and 1/0822/21.

# Direct and imprinted chemical reactivity od plasma treated solutions

**Vít Jirásek**

University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva 12, 1000 Ljubljana

The established terms of plasma-activated water (PAW), plasma-treated saline (PAS), plasma-activated media (PAM, cell culture media) and plasma-treated lactate (PAL, an intravenous fluid) stand for liquids with chemical reactivity imprinted in previous contact with plasma. This post-discharge chemical reactivity is caused by secondary compounds formed when primary reactive oxygen and nitrogen species dissolved in water interact each other or with the compounds of the treated solution. The already well-described mechanisms of peroxynitrite and peroxynitrate formation in PAW lead to formation of reactive, yet short-living species ·OH, $\cdot NO_2$, and O(1Δ) during minutes after the treatment. Reactive chlorine species $OCl^-$, HOCl, $ClO_2^-$, $ClO_3^-$, and $\cdot ClO_2$ were identified in plasma-treated physiological solution (PAS) with a short (~ 1 h) and long (~ 1 day) imprinted reactivity of these oxidizing chlorine species. Last but not least, a recently observed reactivity transfer of HOCl formed in PTM to amino acids, forming mono- and dichloramines with antibacterial activity will be presented. The ability and degree of plasma activation of these liquids is highly dependent on the character of discharge reactor configuration and gaseous mixture used. From the point of view of the agriculture applications, reactors treating larger liquid volumes will be presumably preferred. This comprises DBD discharge in air above liquid surface, flow-through arrangements of pulsed corona discharge in dispersed systems (shower or aerosol, including the electrospray), and flowing films. In this invited lecture, a summary of the most important chemistry of plasma-activated solutions will be given, together with some new findings, and recent works on plasma-activated solutions applicable in agriculture will be briefly reviewed.

# Antifungal efficacy of SDBD cold plasma on dried tomatoes and mechanisms of action

**Junior Bernardo Molina Hernandez (1, 2), Jessica Laika (1), Romolo Laurita (2), Clemencia Chaves Lopez (1)**

(1) Faculty of Bioscience and Technology for Food, Agriculture and Environment, University of Teramo, Via R. Balzarini 1, 64100, Teramo, Italy
(2) Department of Agricultural and Food Sciences, University of Bologna, 47521, Cesena, Italy
(3) Department of Industrial Engineering, Alma Mater Studiorum—University of Bologna, Bologna, Italy

The tomato (Lycopersicon esculentum L. var. Excell and Aranca) is a very perishable and delicate vegetable that is prone to mechanical damage and microbial contamination during shipping, processing, and storage. Along with being consumed as fresh produce, they are also processed into several other products, including pulp, ketchup, sauces, paste, juices, and dried tomatoes. Cold Atmospheric Plasma (CAP) under high surface power density (SPD) values were used to reduce fungal contamination in this type of product. In particular, the surface of the sundried tomatoes was subjected to CAP-NOx treatment applied for 5, 10, 20, and 30 min at 20 cm from the source. The results evidenced that fungal reduction is specie and time treatment-dependent. Furthermore, Pearson correlation analysis ($p = 0.98$) revealed a strong link between spore hydrophobicity and resistance. The considerable effect of CAP-NOx treatment on naturally occurring fungal contamination was confirmed by in-situ tests (76.5% reduction), most likely due to plasma radical-induced cell membrane rupture and cell death. In particular, the treatment resulted in loss of cellular and mitochondrial membrane potential, and a significant rise in intracellular ROS, RNS, calcium, and DNA damage all occurred in conjunction with cell death. Several adaptation mechanisms to combat CAP stress are adopted for the fungi including the accumulation of trehalose, glycerol, chitin, and glucan. Our findings suggested that oxidative stress-dependent through a cascade of processes initiated by membrane depolarization could be used to explain how cold atmospheric plasma induces cell death.

# Numerical simulation and chemical network analysis of plasma-treated water

**Tomoyuki Murakami**

Faculty of Science and Technology, Seikei University, Tokyo, Japan

Low-temperature plasmas have been widely studied in the fields of biomedicine, agriculture, sustainable energy conversion. In these applications, plasma-treated water is gaining increasing attention because they can produce abundant reactive species, whereas the aqueous chemistry is complex and its mechanism is not fully understood. We still have some challenges to reach comprehensive understanding of the nature of plasma-treated liquid chemistry. This study proposes mathematical/numerical approaches to tackle the issue. The complex network analysis based on the graph-theory, one of the information mathematics, enable us to reveal the hidden feature of liquid chemistry through the visualization and centrality-based identification of the reacting network. A newly-developed one-dimensional reaction-diffusion model with hundreds of reaction processes of air-saturated water can simulate the influence of the irradiation of plasma-induced reactive species on the liquid chemistry by quantifying how various plasma species permeate into the liquid and what reactions are triggered.

# Plasma deposition as a possible innovative technology in plasma agriculture

**Fabio Palumbo (1), Antonio Moretti (2), Mario Masiello (2), Mirella de Bellis (2), Stefania Somma (2), Marianna Roggio (3), Pietro Favia (1, 3)**

(1) Institute of Nanotechnology, National Research Council of Italy, Bari, Italy
(2) Institute of Sciences of Food Production (ISPA), National Research Council of Italy, Bari, Italy
(3) Department of Chemistry, University of Bari Aldo Moro, Bari, Italy

The European Green Deal, i.e., the strategy of the European Union for sustainable growth, has among its targets the development of a sustainable food chain to stimulate economy, to improve the quality of people's lives and to protect nature. In this scenario, the "from farm to fork" strategy aims to turn the whole Agro-Food system safer and more eco-compatible by reducing the use of pesticides and fertilizers. In this direction, low-temperature plasma processes recently developed for applications in agriculture and food technologies are very promising. Many promising and innovative processes are nowadays investigated in the plasma enlarged (to life science scientists) community with the aim of addressing such applications objectives. The investigated plasma technologies are mainly based on the development of direct and indirect (e.g. plasma-activated water) of seeds, plants, and soil, with the aim of decontaminating or enhancing germination and growth of plants.

Poor attention has been addressed at the moment to plasma deposition-based processes for agriculture applications. However, a usual practice in agriculture is that of seed coating, by wet methods, with proper chemical compounds to reduce the impact of fungal diseases on the plants during the first growing stages. In particular, sowing coated maize seeds protects seedling plants in their early growth stages. Usually, pesticides, nutrients or bacteria for nitrogen fixation can be used as coatings.

In this presentation, some applications based on seed coatings will be discussed, both at atmospheric and low pressure, mainly for fighting typical cereal mycotoxin-bearing fungi. Such applications consist of a single-step or multilayer deposition of composite coatings containing a fungicide agent.

Furthermore, some perspectives applications will be addressed.

# Properties of plasma treated liquids used in agricultural and water purification applications

**Nikola Škoro, Olivera Jovanović, Amit Kumar and Nevena Puač**

Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia

Many applications of cold atmospheric plasmas (CAP) nowadays are connected to treatments of liquid samples. As CAP induces rich chemistry in active plasma volume creating short- and long-lived reactive species that affect the treated liquid by penetrating and reacting with molecules in the liquid phase. From the application point of view, this type of chemical interaction induced in plasma treatment could be used for liquid activation, i.e., creation of plasma-activated water (PAW) or plasma-activated medium (PAM), or for decontamination of pollutant molecules dissolved in water. For the latter case, plasma can be used as a chemically free advanced oxidation process (AOP) that can efficiently remove various organic micropollutants (OMP) from water. Both applications, PAW creation and plasma decontamination, are within the domain of plasma agriculture research. For all these applications, in order to understand the main processes governing the liquid treatment and to be able to optimize the treatment, clear knowledge of the entangled connection between input parameters, plasma properties, plasma chemistry, and interaction that takes place inside the liquid target is necessary. This is also a prerequisite in order to be able to tune the plasma for different targets. In this work, we will present several kinds of plasma treatments featuring an investigation of both plasma and treated liquid properties and their dependence on operating parameters. Results of treatments of pure and contaminated water (with organic contaminants) were performed by using a high-frequency pin-type atmospheric pressure plasma jet operating with He and Ar. For PAW creation, we demonstrated how the plasma operating in different regimes with He as working gas yield different concentrations of reactive nitrogen and oxygen species. Moreover, we investigated the influence of the working gas as well as sample volume on the RONS concentration and other physico-chemical properties of the activated water. For example, we observed much higher production of $H_2O_2$ in case of Ar plasma than in He. Moreover, scaling-up of the plasma system was investigated – we increased the number of jets and added recirculation of the liquid sample in order to enhance the treatment process. In all systems we precisely determined the power delivered to the plasma. For decontamination processes, this was crucial in order to estimate energy efficiency that is required for comparison to other decontamination processes.

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# Perspectives on the in-line decontamination of food-processing surfaces using cold atmospheric pressure air plasma

**Andreas S. Katsigiannis (1), Nataša Hojnik (2), Martina Modic (2), Danny L. Bayliss (3), Janez Kovač (4), James L. Walsh* (1, 5)**

(1) Centre for Plasma Microbiology, Department of Electrical Engineering and Electronics, University of Liverpool, 9 Brownlow Hill, Liverpool L69 3GJ, United Kingdom
(2) Laboratory for Gaseous Electronics F6, Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia
(3) Processing & Production Research Department, Campden BRI, Station Road, Chipping Campden, Gloucestershire GL55 6LD
(4) Department of Surface Engineering F4, Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia
(5) York Plasma Institute, School of Physics, Engineering & Technology, York Science Park, University of York, York YO10 5DQ, United Kingdom

Low temperature plasmas have shown great promise for microbial decontamination, yet uptake of the technology within the food processing sector has been limited. In this contribution the concept of using Cold Atmospheric pressure Plasma (CAP) for the decontamination of food processing surfaces will be discussed. Such an approach could reduce the need for costly production downtime related to time-consuming cleaning and changeover procedures.

A prototype conveyor-based CAP decontamination system was developed and evaluated against two common foodborne pathogens (Salmonella Typhimurium, Listeria monocytogenes) on stainless steel surfaces and against S. Typhimurium on commercial poly[ether]-thermoplastic poly[urethane] (PE-TPU) conveyor belts, under simulated conditions of a food-processing facility.

A significant level of microbial inactivation was achieved, up to 3.03±0.18 and 2.77±0.71 logCFU/mL reductions of L. monocytogenes and S. Typhimurium respectively within 10 sec total treatment on stainless steel surfaces, and a 2.56±0.37 logCFU/mL reduction of S. Typhimurium within 4 sec total treatment on the PE-TPU material, according to a procedure based on the well-established EN 13697:2015 industrial protocol. In addition, CAP exposure was shown to have a minimal impact on the morphology and composition of the treated surfaces, which is vital for its long-term deployment within a 24 hour production environment.

In summary, CAP was found to be highly effective at eliminating microorganisms on food contact surfaces, while clearly capable of meeting industry expectations in terms of decontamination level and treatment duration. The presentation will conclude with a discussion on the remaining barriers that must be overcome prior to industry adoption of the technology.

# Cold plasma-induced effects in Stevia rebaudiana Bertoni in different experimental models

**Rasa Žūkienė*, Augustė Judickaitė, Vida Mildažienė**

Department of Biochemistry, Vytautas Magnus University, Kaunas, Lithuania

Seed treatment with cold plasma (CP) stimulates seed germination, plant morphometric parameters, biomass production, and disease resistance in different plant species by inducing specific changes in plant biochemical phenotype. It can result in increased amounts of high-value secondary metabolites in plants. However, CP-induced changes are unique for every species and the treatment conditions are still hardly transferable to other plants.

Stevia rebaudiana Bertoni is an economically valuable plant due to its secondary metabolites steviol glycosides (SGs) which are widely used as natural sweeteners. Our research group reported for the first time that pre-sowing seed treatment with CP can be used as a powerful technique for the stimulation of SGs biosynthesis and/or accumulation.

This study aims to overview the main effects of pre-sowing seed treatment with CP (changes in concentrations of SGs, other secondary metabolites, and morphometric parameters) in experimental models with different types of CP, treatment duration/dosage, seed origin, cultivar type, vegetation stage, propagation, and cultivation conditions.

We have demonstrated that a short time (2-7 min) seed treatment with two types of CP (dielectric barrier discharge (DBD) and capacitively coupled (CC) CP) stimulates the biosynthesis/accumulation of SGs up to several folds in all treatments and cultivation conditions except for vegetatively propagated plants. The concentrations of other bioactive compounds such as phenolics, flavonoids, and subsequent antioxidant activity were decreased or unchanged in all treatment conditions when plants were grown in soil but not in an aeroponic system. In aeroponic cultivation conditions, the CP-treated group had significantly higher concentrations of total phenolic compounds (by 43%), flavonoids (by 19%), and antioxidant activity (by 45%) compared to the control. The main economically disadvantageous property of CP-treated groups was lower biomass which can be a result of a trade-off between growth and secondary metabolism in response to CP. These trends were reproducible to varying extents across three cultivars.

It can be concluded that a short-time pre-sowing treatment of seeds with CP can be a powerful tool for the enhancement of biosynthesis/accumulation of SGs in stevia plants. More research is needed to find a way to overcome a biomass decrease in treated plants.

# Study of the different plasma sources for water and seed treatment

**Ludmila Čechová (1), Plamena Marinova (2,3), Evgenia Benova (3), František Krčma (1), Zdenka Kozáková (1)**

(1) Faculty of Chemistry, Brno University of Technology, Brno, Czech Republic
(2) University of Forestry, Faculty of Forest Industry, Sofia, Bulgaria
(3) Sofia University "St. Kliment Ohridski", Clean&Circle Center of Competence, Sofia, Bulgaria

In recent years, plasma technologies found to be very useful not only in material processing, but also in life sciences such as agriculture or medicine. Plasma has unique properties that can cause antibacterial effect and stimulate germination and growth of plants.

In plasma agriculture, we utilize plasma in 2 main ways: 1. direct treatment of seeds and plants and 2. treatment of water and production of Plasma-Activated Water (PAW).

When treating water with plasma discharge, the reactive oxygen and nitrogen species present in plasma can interact with water surface or directly with water molecules in bulk liquid. The resulting product is water with high content of hydrogen peroxide, nitrates and nitrites, which are paramount for sustaining plant growth. While nitrogen is basic nutrient needed for growth and photosynthesis, hydrogen peroxide can stimulate germination of seeds.

In our work, we used 3 different plasma systems specially designed for interaction of plasma with liquids: 1. dielectric barrier discharge with a liquid electrode, 2. microwave cold atmospheric plasma jet above water surface, and 3. pin-hole discharge generating plasma directly in water. Treated water was characterized by pH measurement and determination of $NO_2^-$ and $NO_3^-$ concentrations by UV-VIS spectroscopy. Each plasma system produces different composition of PAW.

In Bulgaria, water from wastewater plants is used for watering fields with crops. This water goes through some water-treating processes but is unsuitable for drinking. Wastewater obtained from water plant as well as tap water were treated with 3 different plasma systems. Treatment time was 1, 2 and 5 minutes and the treated volume was 50 ml in all reactors. We performed a simple toxicity test to assess toxicity of wastewater and plasma-treated wastewater to plants. The number of germinated seeds was counted and the root length was measured. The seeds used were tomato and melon. The number of germinated seeds was counted after 5 days.

Plasma and PAW can be useful tools in stimulation of seed germination. We treated seeds in 2 different variations. First, we prepared different PAW from distilled water with our plasma systems. Wheat seeds were immersed in 50 ml of PAW for 30 minutes. The second variation was treatment of seeds in water. Germination tests were conducted after the treatment. After the germination test, the best-performing variant was put in pots for pot experiments. Pot experiments were conducted in pots filled with substrate with the known composition of macro and micro nutrients. Plants were grown in pots under greenhouse conditions.

# The decontamination of bioaerosols using an in-house rotating dielectric barrier discharge (RDBD) plasma source

**Klaas De Baerdemaeker* (1), Pasquale Isabelli (2), Frank Devlieghere (1) and Romolo Laurita (2)**

(1) Research Unit Food Microbiology and Food Preservation, Department of Food Technology, Safety and Health. Ghent University, Gent, Belgium
(2) Department of Industrial Engineering. Alma Mater Studiorum – University of Bologna, Bologna, Italy

It is generally known that consumption of food products contaminated with pathogenic microorganisms could result in (severe) foodborne illnesses. However, apart from this proliferation via food matrices, the pathogenic species could also spread via air, encapsulated in aerosols. In a food production environment, these airborne characteristics could lead to cross-contamination or affect the health of the operators. In this case, the aerosols could originate from handling contaminated liquid products and processing (e.g., washing) water. Although many systems are already developed to inactivate bacteria present on a food product, the same techniques cannot always be applied to decontaminate the surrounding air.

In this study, it was explored whether cold atmospheric plasma (CAP) could be applied for decontamination of bioaerosols containing Staphylococcus epidermidis cells in a phosphate-buffered saline (PBS) solution. The bioaerosol was injected into a treatment chamber where plasma was generated using an in-house designed rotating dielectric barrier discharge (RDBD) pin-to-plane plasma source. After treatment of several minutes, the aerosol was collected using an impinger with PBS. Finally, the test was repeated with a commercial air purifier based on CAP technology and the bactericidal potential of both devices was compared.

The study showed that high levels of bacterial inactivation ($\geq$ 3.6 log CFU) could be achieved in the aerosol with both devices. On the other hand, ozone, a component harmful to human health, will be produced extensively and released into the environment. Since the bactericidal effect is for a big part dependent on the presence of ozone, inactivation levels decreased when the RDBD set-up was operated at conditions inducing low levels of this plasma component.

# A method to control the energy of free electrons in atmospheric pressure plasma discharges

**T. A. Field* (1), C. Harkin (1), L. Asimakoulas (1), M. Janda (2), K. Hensel (2) and Z. Machala (2)**

(1) Centre for Light-Matter Interactions, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, UK
(2) Division of Environmental Physics, Faculty of Mathematics, Physics and Informatics, Comenius University, Mlynsk´a Dolina, 84248 Bratislava, Slovakia

It appears that the energy of free electrons in atmospheric pressure 'transient spark' discharges can be controlled with a new simple self-pulsing plasma driving circuit that has been developed with an inductor. Optical emission spectra of the discharge show that different ratios of excited states are formed in the discharge as the inductance of the inductor is modified. There is some evidence that the modification of the circuit also changes the plasma chemistry. The addition of an inductor to the driving circuit changes the transient spark discharge from a series of short ($\leq$1 μs) DC pulses with ∼1 kHz repetition frequencies to a series of few cycle ∼ 10 to 100 kHz RF pulses with, again, ∼1 kHz repetition frequencies. The experimental behaviour observed is modelled well by an analytical model of the new circuit.

# Impact of plasma activated water prepared by different systems on the selected soil properties

**Piotr Terebun* (1), Dawid Zarzeczny (1), Michał Kwiatkowski (1), Jana Šimečková (2), František Krčma (3) and Joanna Pawłat (1)**

(1) Department of Plasma Technologies, Lublin University of Technology, Lublin, Poland
(2) Department of Agrochemistry, Soil Science, Microbiology and Plant Nutrition, Mendel University in Brno, Brno, Czech Republic
(3) Institute of Physical and Applied Chemistry, Brno University of Technology, Brno, Czech Republic

The aim of the research was to study the impact of plasma-activated water (PAW) prepared by different plasma systems on the selected soil properties. Four types of soil of various pH were tested. Each soil was mixed and sieved on a 2-mm standard sieve and then pressed into a Kopecky roll. PAW was prepared by 3 atmospheric pressure plasma systems: dielectric barrier discharge plasma jet, gliding arc discharge reactor with audiofrequency micropulses voltage signal and ozonizer exhaust gas bubbling system. In order to compare the systems, the treatment time and power of the reactors were adjusted to obtain the same amount of electrical energy per volume of treated water. PAW was characterized by determining the concentration of selected compounds (hydrogen peroxide, nitrates, nitrites) using colometric methods. Immediately after the plasma treatment, an equal amount of PAW (10% of the weight of the soil) was evenly distributed on the soil surface and then the sample was left for one day. After checking the amount of evaporated water by comparing their weights, the sample was deposited on a layer of filter paper which was constantly wet due to the continuous water supply. The weight of each sample was then checked for a further 24 hours to determine its water absorption. The retention of absorbed water was then checked by depositing the sample on several dry layers of filter paper and by observing its weight for a further 24 hours, periodically depositing the samples on a new dry paper sheets after the weighing. The soil was then mixed again and distilled water was added in a weight ratio of 1:1 to allow the following parameters to be measured: pH, conductivity and oxidation-reduction potential. All results were compared to control samples, in which distilled water was added instead of PAW.

# Influence of low-temperature plasma on the properties of beetroot seeds

**Dawid Zarzeczny (1), Piotr Terebun (1), Michał Kwiatkowski (1), Joanna Pawłat (1), Zdenko Machala (2), Karol Hensel (2) and Agnieszka Starek (3)**

(1) Department of Plasma Technologies, Lublin University of Technology, Poland
(2) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
(3) Department of Biological Bases of Food and Feed Technologies, University of Life Sciences in Lublin, Poland

The study examined the effect of PAW produced by various methods on the germination of red beet seeds. For this purpose, various types of plasma generators were used, changing individual parameters of the plasma treatment process. The tested seeds were subjected to, i.e. direct action of low-temperature plasma and the action of PAW produced by various types of plasma generators.

The conducted research allowed to observe the influence of PAW on the tested seeds. The devices used were the GlidArc reactor (GAD), the DBD reactor and the ozonation device.

Seed germination was conducted in accordance with the ISTA recommendations of 2017. The seeds germination was made by placing them in rows of 20 seeds on each of the papers (BP germination). The seeds were covered with paper and then rolled into a roll. An experiment on seed germination was carried out in a climatic chamber at a temperature of 20±1 °C.

The study was carried out for different plasma treatment times of water and with fixed geometry and power of the discharge systems, using air as the working gas. The effect on germination was evaluated based on the fraction of germinated seeds and their length at 7 and 14 days after treatment. In the case of beetroot, a positive effect on the number and length of germinated seeds was observed, which increased with increasing treatment time. Regardless of the low-temperature plasma generation system used, the effect on seed germination and their properties is positive. PAW obtained with different methods gave similarly good results. At this stage of the work, there are no significant differences between the PAW obtained from the individual devices.

# The effect of PAW on the growth and gene activation of healthy and tomato-mottle-mosaic-virus inoculated tomato seedlings

**Domenico Aceto* (1), Palma Rosa Rotondo (2), Rita Milvia De Miccolis Angelini (2), Angelantonio Minafra (3), Carlo Porfido (2), Roberto Terzano (2), Marianna Ambrico (1) and Paolo Francesco Ambrico (1)**

(1) CNR Institute for Plasma Science and Technology (CNR ISTP), Bari Unit, c/o Department of Physics, University of Bari Aldo Moro, Bari, Italy
(2) Department of Soil, Plant and Food Sciences, University Aldo Moro of Bari, Italy
(3) CNR – Institute for Sustainable Plant Protection – Bari Unit, Via Amendola 122/D, Bari, Italy

Non-chemically based strategies for food production and plant protection are expected to improve the microbial decontamination and the activation of self-defence mechanisms against pathogens along with the increase of biometric and nutraceutical properties of plants. Non-equilibrium Low-Temperature Plasmas (NLTP) represent an emerging technology as a source of Oxygen and Nitrogen reactive species (RONS) and UV radiation that act efficiently in the decontamination, sterilization and chemical modification of surfaces.

However, plasma treatments are mainly confined to the surface of materials, and therefore not able to interact with the entire plant tissue. Thus, different strategies are required for applications, such as the production of plasma-activated media. Among them, water activation by interaction with NLTP seems to be the most cost-effective approach. Exposing water to plasma enriches it with RONS that can have positive effects on plant development. Plasma Activated Water (PAW) can be used for watering crops, soaking seeds, and spraying on foliage, being a sustainable and environmentally friendly alternative to traditional chemical fertilizers and pesticides.

This work aimed to evaluate the role of PAW in enhancing early-stage growth and the activation of defence-related genes in tomato plants.

We produced PAW using a multi-pin double dielectric barrier pulsed discharge applied to distilled water. To control the production of the PAW we monitored the plasma emission. By following $N_2$ SPS and FNS band emissions the plasma temperature was estimated, while hints on the E/N were derived during the Plasma Pulse. The energy deposited in the plasma was monitored by Charge Voltage characteristics. The obtained PAW was characterized in terms of content in reactive species, i.e. $H_2O_2$, $NO_3^-$, $NO_2^-$, pH and ORP.

Seedlings of tomato cv. Regina were transplanted in commercial peat moss soil at two true-leaves stages. Pots were kept in a glasshouse box at constant temperature (25 °C) and an 18-h photoperiod. Tomato plants were irrigated with distilled water or PAW. Plants grown using the standard procedure were used as control. Negative control plants were also cultivated using the conventional procedure. Half of the samples were also inoculated with Tomato Mottle Mosaic Virus (TMMV). The results on the plant growth were characterized in terms of biometric parameters such as foliar coverage, chlorophyl contents, and stem length. The leaf macro/micronutrients were characterized using micro-X-ray imaging. To evaluate possible induction of defence responses, four different defence-related genes [phenylalanine ammonia-lyase (PAL), pathogen-related protein 1 (PR-1), lipoxygenase (LOX), and catalase (CAT)] were selected and used for gene expression profiling by reverse transcription-quantitative polymerase chain reaction (RT-qPCR) at an early stage after treatment with PAW and after artificial inoculation with the virus (TMMV). We observed that plants irrigated by PAW showed better biometric parameters and were able to resist the viral infection compared with the untreated plants, showing stem lengths almost similar to the not-inoculated ones, even though foliage coverage and macro/micro contents were lower.

# On the effectiveness of dielectric barrier discharge treatment against phytopathogenic fungi

**Paolo F. Ambrico (1), Domenico Aceto (1), Giorgio Dilecce (1), Marianna Ambrico (1), Palma Rosa Rotondo (2), Milvia De Miccolis Angelini (2), Caterina Rotolo (2), Francesco Faretra (2)**

(1) CNR Institute for Plasma Science and Technology (CNR ISTP), Bari Unit, c/o Department of Physics, University of Bari Aldo Moro, Bari, Italy
(2) Department of Soil, Plant and Food Sciences, University Aldo Moro of Bari, Italy

The inhibitory effect of a square wave modulated plasma (duty cycle 20%) Volume Dielectric Barrier Discharge (VDBD) at atmospheric pressure in ambient air was evaluated on conidial germination of different fungal species: Botrytis cinerea, Monilinia fructicola, Aspergillus carbonarius, Fusarium graminearum and Alternaria alternata. Several factors potentially influencing the efficacy of plasma treatment were studied, such as total treatment time, applied voltage, and agarized medium composition. As previously observed the inhibitory effect of the treatment progressively increased with the extension of the time of exposure to VDBD and decreased with the complexity of cellular structures of the analyzed fungal species. The uniformity of the plasma, depending on the applied voltage, must be taken into consideration since in filamentary plasma. Factors that could be crucial are the selected applied voltage but also the samples under processing. In in vitro experiments, one crucial point is the response of agarized media (Water Agar (WA), Glucose Agar (AG), Malt Extract Agar (MEA), and Potato Dextrose Agar (PDA)) to the electrical applied field that can strongly influencing plasma generation. To monitor those possible effects, charge-voltage characteristics were monitored for each experiment, showing a different behaviour for different media. To better understand this point agarized media morphology was also analyzed cryo-Scanning Electron Microscopy (cryo-SEM) images and correlated to the different plasma electrical responses in terms of electrical impedance and Charge transfer characteristics in the plasma phase. In the tested experimental conditions, complete inhibition of conidial germination was achieved with different treatment times. For instance, 5 s of total treatment time, inhibited the conidial germination of B. cinerea completely, while 20 s were necessary for both M. fructicola and F. graminearum instead, the total inhibition of conidial germination for A. alternata was reached at 60 s of VDBD treatment. Aspergillus carbonarius was completely inhibited after 180 s of treatment, although the conidial germination was affected by the agarized media used. Optical emission spectroscopy of $N_2$ molecular bands in order to derive information on gas plasma temperature and the reduced electric field (E/N) was also derived. Nevertheless, we must point out that in a side experiment performed in humid air, the comparison between E/N derived from

the discharge and direct measurements of E-Field obtained using the Electric Field Induced Second Harmonic generation (E-Fish) showed that in certain conditions the assumed local thermal equilibrium is not satisfied inducing an error in an estimation of plasma-induced E-Field.

# Nonthermal plasma at atmospheric pressure with aerosols: applications in agriculture and biomedicine

**Neda Babucić*, Nevena Puač, Nikola Škoro**

Institute of Physics, University of Belgrade, Pregrevica 118, 11080, Belgrade, Serbia

Due to its diverse usage in water purification, wound treatment with plasma-activated water (PAW) and agriculture, low-temperature plasma (LTP) applications are being researched. Increasing the flux of reactive species from the plasma is one of the main difficulties in the interaction between plasma and water. A high surface-to-volume ratio, an increase in the contact area for a given amount of water, and the inclusion of micrometer-scale aerosol droplets immersed in plasma all have the potential to speed up chemical reactions between plasma in the gas phase and liquid. The plasma-aerosol arrangement is enabling deeper scientific understanding of a complicated subject with possibly hundreds of transient and non-equilibrium chemical reactions, in addition to the development of plasma-liquid applications. In this sense, we started putting together an experiment and completed the first phase of setting up using a microwave (MW) plasma source to treat aerosols. To better understand gas-liquid reactions of high chemical reactivity, the setup will allow for the analysis of the plasma, interaction between the plasma and droplets, and characterization of treated water. MW plasma is currently conducted without the addition of aerosols using an Argon flow from 1 to 7 slm. Images of the plasma and optical emission spectroscopy data were used to determine how far away from the source reactive species play a key role. In this configuration, after adding aerosol to the reactive volume, we will be able to evaluate the impact of droplets on the plasma. The major goal is to comprehend plasma-aerosol interactions better because they can be involved in the treatment of biology samples when applied at atmospheric pressure.

# Degradation of micropollutants in secondary wastewater effluent using nonthermal plasma-based AOPs

**Changtao Chen (1, 2, 3), Kristof Demeestere (3), Anton Nikiforov (2), Stijn Van Hulle (1)**

(1) LIWET, Laboratory for Industrial Water and EcoTechnology, Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Campus Kortrijk, Sint-Martens-Latemlaan 2B, B – 8500 Kortrijk, Belgium
(2) RUPT, Research Unit Plasma Technology, Department of Applied Physics, Faculty of Engineering and Architecture, Ghent University, Sint-Pietersnieuwstraat 41, B4, B – 9000 Ghent, Belgium
(3) EnVOC, Research Group Environmental Organic Chemistry and Technology, Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, B – 9000, Ghent, Belgium

Emerging micropollutants (µPs) appearing in water bodies endanger aquatic animals, plants, microorganisms and humans. Most countries are equipped with very basic wastewater treatment systems to accommodate the populations' needs before discharge into the environment, which may be insufficient to generate treated effluent to be reused in agriculture. The nonthermal plasma-based advanced oxidation process is a promising technology for eliminating µPs in agricultural wastewater but still needs further development in view of full-scale industrial application. A novel cascade reactor design which consists of an ozonation chamber preceding a dielectric barrier discharge (DBD) plasma reactor with a falling water film on an activated carbon textile (Zorflex®) was used to remove a selection of µPs from secondary municipal wastewater effluent. Compared to previous plasma reactor, molecular oxidants degraded micropollutants again in an ozonation chamber in this study, and the utilization of different reactive oxygen species (ROS) was improved. A gas flow rate of 0.4 standard liters per minute (SLM), a water flow rate of 100 mL per minute, and a discharge power of 25 W are identified as the optimal plasma reactor parameters, and the µP degradation efficiency and electrical energy per order value (EE/O) are 84-98% and 2.4-5.3 $kW/m^3$, respectively. The presence of ROS during plasma treatment was determined in view of the µPs removal mechanisms. The degradation of diuron (DIU), bisphenol A (BPA) and 2-n-octyl-4-isothiazolin-3-one (OIT) was mainly performed in ozonation chamber, while the degradation of atrazine (ATZ), alachlor (ALA) and primidone (PRD) occurred in an entire cascade system. The ROS not only degrade the µPs, but also remove nitrite (90.5%), nitrate (69.6%), ammonium (39.6%) and bulk organics (11.4%). This study provides insights and optimal settings for an energy-efficient removal of µPs from secondary effluent using both free radicals and molecular oxidants generated by the plasma in view of a full-scale application.

# The role of melanin in the response of fungi to low-temperature plasma exposure

**Palma Rosa Rotondo (1), Caterina Rotolo (1), Marianna Ambrico (2), Stefania Pollastro (1), Francesco Faretra (1), Paolo Fracesco Ambrico (2), and Rita Milvia De Miccolis Angelini* (1)**

(1) Department of Soil, Plant and Food Sciences, University Aldo Moro of Bari, Italy
(2) CNR Institute for Plasma Science and Technology (CNR ISTP), c/o Department of Physics, University of Bari Aldo Moro, Bari, Italy

Conventional methods for plant disease control have often shown limitations in environmental impact, animal and human safety, as well as in economic costs and efficiency. Low-temperature plasma (LTP) is currently proposed as a new green technology for safe and sustainable food production raising considerable interest in recent years.

Recent investigations on the inhibitory effect of plasma treatments against fungal plant pathogens revealed differences in survival rates of spores from different fungal species that require different treatment times to reach significant inhibition of spore germination, reduction of cell viability and morphological alterations of cell surface up to spore destruction. These differences could be related to the fungal cell wall thickness, structure and composition. In this work, the possible protective role of melanin against inactivation by plasma was investigated. Normally pigmented conidia of a wild-type strain of Botrytis cinerea and albino conidia from two UV-induced mutants were phenotypically and genetically characterized and compared for their in vitro responses to exposure to different plasma sources [Surface Dielectric Barrier Discharge (SDBD), Volume Dielectric Barrier Discharge (VDBD), and plasma-jet (Atmospheric-Pressure Plasma Jet, APPJ)].

B. cinerea mutants showed cream-coloured conidia and regularly pigmented sclerotia and carried a nonsense single-point mutation creating an in-frame stop codon in the bcpks13 gene, a key gene for conidial melanogenesis. Melanines from wild type pigmented conidia, based on their physio-chemical and spectral properties, were assigned to DHN melanins, and were absent or very little in the albino mutants.

Mutants showed higher sensitivity to plasma treatments compared to the wild-type strain suggesting that melanin and other pigments could affect fungal response to plasma exposure. Albino conidia were significantly inhibited (> 81%) after only 1 min of SDBD exposure, while at least 10 min treatment were required for the wild-type one. All the strains were completely inhibited after 3 min of APPJ exposure, while significant differences among the strains were observed at shorter treatments times (5 sec). VDBD plasma caused the complete inhibition of conidia germination after just 10 sec or 30 sec of exposure in albino and wild-type strains, respectively.

# Research on the potential use of cold plasma treatments on eggplant seeds

**Mihai Gidea, Monica Magureanu**

University of Agronomic Sciences and Veterinary Medicine of Bucharest, Romania
National Institute for Laser, Plasma and Radiation Physics, Romania

The continuous growth of the population has also determined an increase in the demand for food; in order to respond to this challenge, the productivity of agricultural crops must be increased. In this context, in order to complement the conventional techniques of improving, fertilizing and maintaining crops, it is also necessary to use alternative methods that allow obtaining uniform crops with great vigor. This category also includes plants grown in protected spaces (greenhouses), especially vegetables, which cannot be sown directly and which, after the first stage of growth, are transplanted to obtain seedlings, which will later be planted and will result in plants that will produce. One of the methods to help plants overcome these problems is cold plasma treatment. In order to test the impact of the use of cold plasma treatments on the growth and development of eggplant plants, a bifactorial experiment was carried out in which factor A was the treatment time and B was the discharge voltage factor. Cold plasma treatment was performed in a coaxial reactor at room temperature and atmospheric pressure. After treatment, seed germination and early plant growth were monitored. Following the research, the main indicators of germination and plant growth were determined. The results showed an increase in the germination rate of eggplant seeds and an increase in the fresh biomass accumulated in the plants. Increasing the discharge voltage in all cases led to an increase in the germination parameters and increasing the treatment duration at low discharge volumes had a stimulatory effect while at high voltages, they had an inhibitory effect. In the case of discharge voltages over 17 kV, there were decreases in the values of the tested parameters. Still, also in these cases, there were significant increases compared to the untreated control Plasma treatments can be used as an effective alternative method for treating eggplant seeds.

# Degradability improvement of the olive mill wastewater by high voltage electrical discharge plasma (HVED)

**Mia Ivanov (1), Tomislava Vukušić Pavičić* (1), Višnja Stulić (1), Klara Kraljić (1), Tibela Landeka Dragičević (1), Zoran Herceg (1)**

(1) Faculty of Food Technology and Biotechnology, University of Zagreb, Zagreb, Croatia

Olive mill wastewater presents an environmental problem when released in nature due to high phytotoxicity, antimicrobial properties and genotoxicity. Because of its complex composition, the degradation of olive mill wastewater was recently a very important research topic. To improve the degradability of the olive mill wastewater, high voltage electrical discharge plasma (HVED) is used. HVED is a non-thermal technology that is considered promising for wastewater removal due to its fast removal rate. In this study, the aim was to investigate the influence of HVED on the degradation of physico-chemical parameters of olive mill wastewater. Plasma was generated in the gas phase at the frequency of 60 Hz, voltage 50 kV and treatment time 20 min, during which gases air and $N_2$ were changed to determine the influence on physico-chemical parameters. Total organic carbon (TOC) (mg/), total phenolic content (TPC) (mg/L), pH, conductivity (µS/cm), nitrates ($NO_3$) (mg/L) and nitrites ($NO_2$) (mg/L) were measured before and after the treatment to determine the degradability of the olive mill wastewater. Obtained results showed a great possibility of HVED application in olive mill wastewater degradation. Furthermore, research on the chemistry of degradation intermediates will be of high interest.

# Argon plasma pin-type jet for water treatment and biological applications

**Olivera Jovanović*, Nevena Puač, and Nikola Škoro**

Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia

A non-thermal Ar plasma jet operated in the kHz regime was used to generate reactive oxygen and nitrogen species (RONS) in water and produce plasma-activated water (PAW). We have developed a plasma jet in pin electrode configuration that generates a streamer discharge. The distance between the powered electrode and water placed in a vessel below the plasma device was 10 mm. As working gases, we used argon and an admixture of argon and synthetic air (3%). Total gas flow was kept at 1 slm. During treatments of 5, 10, and 20 minutes, 15 ml of distilled water was treated. In order to identify and determine the spatial distribution of excited reactive species produced by plasma-liquid interaction, we used spectrally resolved imaging and optical emission spectroscopy. To examine the efficacy of plasma treatment, liquid diagnostics, including electrical conductivity, pH, and RONS measurements, were carried out immediately after treatments. Concentrations of nitrate and hydrogen peroxide were determined photometrically by using a spectrophotometer. The findings of the optical characterization and measurement of the physicochemical properties of PAW indicated a correlation between RONS formation in the gas phase and in treated water. The obtained results demonstrated that the quantities of measured reactive species in water may be adjusted for the specific application in biotechnology by varying the treatment parameters and employing a single plasma jet.

# The effect of plasma-activated water long term application on physical chemical soil properties

**František Krčma (1), Jana Šimečkova (2)**

(1) Brno University of Technology, Faculty of Chemistry, Purkyňova 118, 612 00 Brno, Czech Republic
(2) Mendel University in Brno, Faculty of AgriSciences, Zemědělská 1, 613 00 Brno, Czech Republic

Plasma-activated water (PAW) applications in agriculture deals into two main directions. The first one is application on seeds with aim to improve their germination and early phase of groove. Less investigated is PAW application on plants as fertilizer and antibacterial/antifungal agent. PAW is applied by spraying on plant leaves and some part also terminates on soil. However, effects on plants are generally positive, there is leak of knowledge what will happen with soil affected by long-term PAW application. Soil itself is very complex system combining inorganic and organic compounds with huge number of living organisms and all of these components can be affected by PAW.

The aim of presented work is extension of our recent study on 13 different soils. PAW was prepared from distilled water using DBD system with liquid electrode. PAW and distilled water (as reference) were self-absorbed by the soil samples (90 g of the soil samples pressed by 5 atmospheres in Kopecky cylinders) for 48 hours. Samples were put on the glass covered by a filter paper which ensured continuous water delivery to sample from its bottom. Each sample had independent water source, so cross influence among samples was impossible. All cylinders were covered by filter paper to avoid water evaporation during the two days sorption. Next 12 days were samples dried at laboratory conditions, the air conditioner was used to accelerate drying process. This scheme was 6 times repeated. All was carried out in six replications.

Tap water absorption of three samples from each group was tested by saturation on the glass covered by a filter paper with continuous tap water delivery. The absorption was measured at selected times by sample weighing. In next step, the fully water-saturated soil samples were put on the dry filter paper (4 layers) to monitor water-holding capability, this was measured at selected times by sample weighing. Soil from the second group of samples was removed from the Kopecky cylinders individually, fully dried and stored at ambient laboratory conditions up to their processing. An amount of 10 g of the soil was shaken with 25 ml of boiled distilled water or of 1 M solution of potassium chloride. The colloid solution was kept in a closed vessel for 24 hours at laboratory temperature. After that, the solution was shaken again, and solution pH was measured. The pH values measured using distilled water reflect free proton concentrations in the soil, while pH values measured using the KCl solution also reflect bounded protons in the sorption system of the soil.

The obtained results show that PAW application is strongly soil dependent and thus further experiments will be needed to be able generalize results about PAW application.

# Inactivation of Escherichia coli and Staphylococcus aureus by cold plasma for disinfection of surfaces in food industry

**Aleksandra Lavrikova* (1), Helena Bujdákova (2), Karol Hensel (1)**

(1) Division of Environmental Physics, Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
(2) Department of Microbiology and Virology, Faculty of Natural Sciences, Comenius University, Bratislava, Slovakia

Food contamination has been a serious public health issue resulting in thousands of deaths each year and a cause of huge economic losses worldwide. The occurrence of foodborne pathogens at any stage of food processing complicates regulations of food safety and hygiene. Inadequate sterilization can provoke the attachment of aerobic bacteria forming biofilms that are more resistant to antimicrobials. For example, pathogenic E. coli from natural foods and food products often causes severe diarrhea; S. aureus is one of the most important pathogens and a leading cause of foodborne intoxication worldwide. Cold plasma is a sustainable alternative to conventional methods of microbial contamination in food processing. It has been found to be effective in inactivating microorganisms on food or food contact surfaces by means of direct and indirect (plasma-activated liquids) application.

The present study demonstrated the capability of cold plasma for water and surface bio-decontamination. Air transient spark (TS) and streamer corona (SC) discharges were applied to bacteria in planktonic and biofilm forms, respectively. The plasma-induced effects were systematically compared on standard strains of E. coli CCM3954 and S. aureus CCM 3953. A circulating system in TS discharge was used for the treatment of planktonic bacteria in saline solution. Indirect treatment via plasma-activated saline (PAS) showed insignificant bacteria inactivation. Despite this, direct treatment for 15 min completely inactivated E. coli and caused a 3.5 log reduction of S. aureus. The physicochemical properties of PAS (temperature, pH, electrical conductivity, ORP, $H_2O_2$, $NO_2^-$, $NO_3^-$, •OH, $ONOO^-$, $Cl^-$, $ClO^-$) were evaluated to better understand the complex molecular mechanisms of the plasma-bacteria interaction pathways. Thus, post-treatment storage led to the increase of bactericidal effects related to the ORP increase. Unique inactivation pathways for Gram-opposite bacteria were proposed based on the evaluation of metabolic activity, membrane integrity, accumulation of intracellular ROS, and morphological changes. The pulsed SC discharge was used for the treatment of biofilms. Both E. coli and S. aureus biofilms underwent significant loss of biofilm biomass, suppression of metabolic activity, and removal from polystyrene or glass substrates. The results proved a large potential of cold plasma to improve the safety of food production and storage.

# Impact of non-thermal plasma on lipid oxidation: identification of key reactive species

**Danyang Liu (1), Charlie Van Paepeghem (1), Joke Sierens (1), Mehrnoush Narimisa (2), Anton Nikiforov (2), Nathalie De Geyter (2), Kristof Demeestere (3), Bruno De Meulenaer* (1)**

(1) Research Group NutriFOODchem, Department of Food Technology, Safety and Health, Ghent University, Coupure Links 653, 9000 Ghent, Belgium
(2) Research Unit Plasma Technology (RUPT), Department of Applied Physics, Ghent University, Sint-Pietersnieuwstraat 41, 9000 Ghent, Belgium
(3) Research Group EnVOC, Department of Green Chemistry and Technology, Ghent University, Coupure Links 653, 9000 Ghent, Belgium

Non-thermal plasma is a mild processing technology for food preservation. Its impact on lipid oxidation was investigated in this study. Stripped methylesters were considered as a basic lipid model system and were treated by a multi-hollow dielectric barrier discharge (MDBD). In dry air plasma, $O_3$, $\bullet NO_2$, $\bullet NO_3$ and $^1O_2$ were identified as the main reactive species reaching the sample surface. Treatment time played the most prominent role in inducing lipid oxidation, followed by (specific) power input of the treatment and plasma-sample distance. In humid air plasma, less $O_3$ was detected, but ONOOH and $O_2NOOH$ were generated and presumed to play a role in lipid oxidation. Ozone mainly resulted in the formation of carbonyl substances via the trioxolane pathway, while reactive nitrogen species (i.e., $\bullet NO_2$, $\bullet NO_3$, ONOOH and $O_2NOOH$) led to the formation of hydroperoxides. The impact of short-living species (e.g., ●O, ●N, ●OH and ●OOH) was restricted in general since they dissipated too fast to reach the sample. ●NO, $HNO_3$ and $H_2O_2$ did not induce lipid oxidation. All the reactive species identified in this study were associated with the presence of $O_2$ in the input gas.

# Future agriculture with green fertilizers produced by non-thermal plasma-activated water technology?

**Zdenko Machala, Saeed Kooshki, G. B. Ndiffo Yemeli*, Mário Janda, and Karol Hensel**

Division of Environmental Physics, Faculty of Mathematics, Physics and Informatics, Comenius University, Mlynská Dolina, 842 48 Bratislava, Slovakia
*now with GREMI, UMR 7344, CNRS/Université d'Orléans, 14 rue d'Issoudun, 45067 Orléans Cedex 2, France

Non-thermal (cold) plasma technologies bring new application potential in multiple areas, including biomedicine and agriculture. Cold plasmas or plasma-activated liquids can be used as green alternatives to conventional chemicals in agriculture to improve yields, increase plants' robustness, and reduce the need for pesticides, which introduces a new dimension in sustainable agriculture with a lower negative environmental impact.

One area of cold plasma agricultural applications is the treatment of seeds by plasma or plasma-activated water (PAW) inducing physical and biochemical changes in seeds, which improve their germination and early plant growth [1-2]. Plasma/PAW seed priming can lead to significant improvement of the plant product yield, as shown experimentally on peas [3]. PAW solutions can be directly applied to growing agricultural plants by irrigation into the soil, by spraying on leaves, or by hydroponics. PAW has been documented as a plant growth promotor, hence reducing the use of chemical fertilizers, especially improving the plant early-stage development and growth, and influencing their physiological parameters, without causing any harmful DNA damage [3-4].

Plasma treatment can be applied for organically and microbially polluted agriculture wastewater, leading to both pollution/odor reduction and sanitizing, with a potential water reuse as fertilizer. Moreover, plasmas in atmospheric air lead to nitrogen fixation into (NOx) [5] and nitrites/nitrates ($NO_2^-$/$NO_3^-$) formation in water [6]. We extensively study the physico-chemical and transport processes occurring at the plasma-liquid interface, which allows us tuning the process towards the desired microbial disinfection [6] or fixing nitrogen in PAW.

Nitrogen fixation is an emerging topic with great environmental potential in sustainable agriculture. Various forms of nitrogen represent an alternative to ammonia-based fertilizers produced globally by Haber-Bosch process, consuming almost 2% of the world's total energy production and utilizing 3-5% of the total natural gas. The key novelties of nitrogen fixation into PAW are relatively low energy costs and a direct transport of the produced $NO_x$/$HNO_x$ into water, including agricultural wastewater or livestock slurry. This can make a valuable green fertilizer by trapping fugitive gaseous ammonia as $NH_4NO_3$ [7]. It also prevents nitrogen losses into the atmosphere and reduces greenhouse gas emissions from decaying processes in agricultural waste. The cold plasma/PAW strategy results in producing a sanitizer as well as a green fertilizer and plant growth stimulant.

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# Research on the reuse of plasma treated wastewater in agriculture

**Florin Bilea (1, 2), Marius Cicirma (1, 3), Monica Magureanu* (1)**

(1) National Institute for Lasers, Plasma and Radiation Physics, Magurele, Romania
(2) University of Bucharest, Faculty of Chemistry, Bucharest, Romania
(3) University of Bucharest, Faculty of Biology, Bucharest, Romania

Water reuse becomes increasingly important in water management, in the context of water scarcity and rising demand. Most reuse applications are related to irrigation and several countries already established regulations regarding the quality of the reclaimed water [1]. Contaminants of emerging concern, which are not regulated under the current environmental legislation, may have damaging effects on plants and may also affect human health either directly, by consumption of crops irrigated with polluted water, or indirectly, by inducing antibiotic resistance in soil bacteria. Thus, efficient and economical treatment technologies are needed to ensure the quality of water intended for agricultural reuse.

This work shows the detrimental effect of sulfamethoxazole (SMX) on tomato seeds and evaluates the potential of plasma treatment to degrade this compound and thus to reduce the toxicity to plants induced by solutions containing it. SMX is a sulfonamide antibiotic which inhibits the folate-specific metabolic processes for bacterial growth. It acts similarly in plants, disrupting the folate biosynthesis and thus inhibiting plant development.

A corona discharge with gas recycling [2], operated in oxygen with high voltage pulses of 18 kV and 100 ns at 25 Hz, was used for the treatment of aqueous solutions containing SMX (0.1-0.5 mM) prepared in tap water. Tomato seeds were incubated with untreated 0.25 mM solution (SMXT0), solutions treated by plasma for 5, 20 and 30 min (SMXT5, SMXT20, SMXT30) and tap water as negative control ($H_2O$). The SMXT5 solution still contains 24% of the target compound (0.06 mM), while for the longer treatment times SMX was not detectable any more. The SMXT0 and SMXT5 samples induce a slight delay in seed germination and greatly inhibit root growth. In the $11^{th}$ day after sowing, the roots of plants grown with SMXT0 were on average more than three times shorter than the control ones. Short duration plasma treatment (SMXT5) led to an evident improvement in root growth, but the difference as compared to clean water remained statistically significant. In contrast, solutions treated for longer time (SMXT20 and SMXT30) promote growth, and the mean root length of the seedlings showed significantly higher values as compared to control samples (up to 40% increase). This positive effect might be caused by active species produced in the liquid under the action of plasma, together with complete elimination of the contaminant.

Although the energy efficiency for the degradation is rather high, i.e. 25 g/kWh, the cost of plasma treatment remains a major challenge from the point of view of practical application. Another issue that requires further study is the uptake of contaminants or their degradation products into the plants.

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# Extraction of valuable compounds from microalgae using plasma and pulsed electric field treatment

**L. Marcinauskas* (1, 2), K. Jonynaitė (3), R. Uscila (1), S. Keršulis (3), A. Stirkė (3), Ž. Kavaliauskas (1), M. Aikas (1), V. Stankevič (3)**

(1) Plasma Processing Laboratory, Lithuanian Energy Institute, Kaunas, Lithuania
(2) Kaunas University of Technology, Kaunas, Lithuania
(3) Department of Functional Materials and Electronics, Center for Physical Sciences and Technology, Vilnius, Lithuania

The main aim was to investigate the effect of a combination of pulsed electric field (PEF) and gliding arc discharge (GAD) plasma treatment on microalgae and determine the influence of treatment parameters on the extracted concentrations of proteins. The GAD plasma and PEF technologies were used for the treatment of Chlorella vulgaris microalgae. The Chlorella vulgaris were cultivated in a photobioreactor using BG-11 medium for 7 days before harvest. The plasma irradiation of the algae suspension was done using air plasma. The duration was set for 300 s using different power supply output voltages. PEF treatment was performed using a high-voltage exponential wave pulse generator with 1 and 10 pulses (pulse duration was ~10 μs, repetition frequency 1 Hz and electric field strength 23-25 kV/cm). The elemental composition of air plasma was investigated using an acousto-optic emission spectrometer. The nitrite, nitrate, and hydrogen peroxide concentrations in algae suspension before and after treatment were investigated using commercial test and protocols. The influence of GAD plasma and/ or PEF treatment parameters on the electrical conductivity, cell permeability, pH values, optical density, content and type of extracted proteins were investigated.

It was demonstrated that the chlorophyll content, cell density, pH values, conductivity, and viability of microalgae depended on the GAD plasma and PEF treatment conditions very strongly. The increase of the plasma discharge voltage enhanced the amount of nitrogen species in air plasma and resulted in higher concentrations of nitrate and nitrite in microalgae suspension and supernatant. The pH values were reduced, and the electrical conductivity of microalgae suspension was increased with the increase of discharge power. No changes in protein concentrations were observed when considering the direct effect of plasma on the BSA protein suspension. However, the increase in signal intensity and the blue shift of the peak observed in the fluorescence spectra are indicative of a plasma-induced conformational change in the protein. The extracted protein concentration from microalgae was slightly enhanced when the combination of GAD plasma and PEF treatment was used. However, the increase of the plasma discharge power up to some critical values started to reduce the concentrations of extracted proteins. The researchers have shown that by choosing the optimal GAD plasma and PEF treatment parameters, the concentration of extracted proteins can be increased up to 20 %.

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# Low-pressure microwave air plasma for spices decontamination

**Cristina Muja* (1), Abderrahmane Kais (1), Manon Soulier (1), Youcef Fermi (1), Thomas Maho (1), Philippe Belenguer (2) and Philippe Guillot (1)**

(1) DPHE Laboratory, INU J.F. Champollion, University of Toulouse, Albi, France
(2) LAPLACE Laboratory, INP, CNRS, University of Toulouse, Toulouse, France

The global spices and seasonings market was valued at 16.59 billion euros in 2021 and is projected to grow to 23.76 billion euros by 2029. Traded spices and herbs may be subjected to conditions which favor microorganisms' proliferation before arriving to consumers. Their contamination can be caused by microorganisms present naturally on plants (epiphytic microflora) or by other microorganisms during harvest, drying, transport and storage. Furthermore, a great part of these products is harvested in warm and moist regions, which contributes to microbiological contamination. If left untreated, these herbs and spices could result in rapid spoilage of products or generate food-borne illnesses.

In this work, we examined the use of a low-pressure microwave air plasma discharge as a potential solution for the decontamination of spices. A microwave collisional plasma source (HI-WAVE, SAIREM, France) distributed in a three-dimensional network was used in a 40 liters reaction chamber to obtain a homogeneous discharge. This source was designed to achieve an optimized impedance transition from 50 Ω technologies to the plasma impedance for gas pressure ranging in several $10^{-1} \sim 10^{-2}$ mbar. Plasma characterization was performed using an optical spectrometer (SpectraPro HRS-750). These measurements provided basic plasma characteristics – optical emission, electron temperature and charged species intensities distribution.

Black pepper (Piper nigrum) grains were used as a spice model matrix for the decontamination assays. The biocidal efficiency will be evaluated using the mesophilic flora present in the samples. Furthermore, Bacillus subtilis endospores inoculated on glass carriers and on pepper grains were used to assess the sporicidal effect. Finally, the effect of the plasma treatment on the physicochemical characteristics – e.g., color, moisture content and piperine content were investigated.

# Atmospheric pressure plasma for fresh juice preservation

**J. Pawlat (1), P. Terebun (1), D. Zarzeczny (1), M. Kwiatkowski (1), A. Starek (2)**

(1) Lublin University of Technology, Lublin, Poland
(2) University of Life Sciences in Lublin, Lublin, Poland

Mini glide arc reactor (GAD) is known for its versatility and ability to work with required types of substrate gas. Plasma treatment leads to generation of active species such as ions and electrons, free radicals and reactive oxygen and nitrogen species (RONS). These species can act as inhibitors of bacterial and fungal growth and, in the case of food, they can influence nutritional and organoleptic properties of the target.

GAD was used to treat fresh tomato and carrot juices. Impact of the plasma treatment on the quality, physicochemical properties and its ability to inactivate the background bacteria, yeasts and molds was investigated. The extension of preservation time during the cold storage was noticed, however it was distinctively shorter in the case of carrot juice. In the case of tomato juice, results were satisfactory: more than 3-log reduction of the number of microorganisms was achieved after 5 min. of plasma treatment: 3.45-log CFU/ml reduction for the total aerobic mesophilic bacteria colonies, 3.55-log CFU/ml reduction for yeast, and 3.32-log CFU/ml reduction for molds were obtained. The treatment had only a subtle impact on the pH of tomato juice. A positive effect on the total carotenoid and lycopene content was observed, with a 13% and 11% increase, respectively. A 5% loss of vitamin C content was noticed after 5 min. GAD treatment in the case of tomato juice.

# Influence of plasma seed treatment on sunflower growth traits

**Ioan Radu (1, 3), Ioana Florescu (1), Andrei Teodoru (1), Lorena Gurau (1), Constantina Chireceanu (1), Florin Bilea (2) and Monica Magureanu (2)**

(1) Laboratory of Harmful Organisms, Research and Development Institute for Plant Protection, Bucharest, Romania
(2) Department of Plasma Physics and Nuclear Fusion, National Institute for Lasers, Plasma and Radiation Physics, Atomistilor, Magurele, Romania
(3) Faculty of Agriculture, University of Agronomic Sciences and Veterinary Medicine of Bucharest, Bucharest, Romania

In the last years, plasma seed and plant treatment technology has risen to sustain an eco-friendly agriculture. The aim of this study was to investigate the effect of treatment of sunflower (Helianthus annuus L.) seeds by a DBD plasma in air and monitors the plants grown from plasma-treated seeds throughout their entire lifespan. 30 g of seeds were packed in a DBD reactor operated in air and treated in plasma for 10 min. The electrical discharge was operated with sinusoidal voltage of amplitude Vm = 16 kV and frequency ν = 50 Hz. In laboratory experiment shoot length of plasma-treated plants was significantly larger than for the untreated ones, while the values of the root lengths were similar. Plasma treatment enhanced biomass accumulation by approximately 30% (fresh weight) and 20% (dry weight). Results obtained in the field showed a positive impact of plasma exposure with respect to capitulum size, number of seeds per capitulum and mass per thousand seeds, thus resulting an increase in crop yield.

# Influence of cold plasma on agriculture applications of selected multi-species grass sward

**Lokeswari Ramireddy (1), Peter Dobbyn (1), Sean Kelly (1), Tommy Boland (2), Paula Bourke (1)**

(1) Plasma Research Group, Institute of Food and Health, School of Biosystems Engineering, University College Dublin, Dublin 4, Ireland
(2) UCD Lyons Farm, School of Agriculture and Food Science, University College Dublin, Dublin

Agriculture applications of cold plasma are under investigation to support sustainability along the farm-to-fork food chain. The treatment of a range of seeds has been studied to date and there are many factors that require evaluation. Some of these include species and seed type, seed dimensions, short- and long-term effects on both seeds and subsequent plant performance in a range of conditions. Seed and plasma process compatibility require evaluation for a particular plasma set up. The current study aimed to compare six different seed types and to investigate the impact of atmospheric pressure plasma on the germination and seedling development of six different seeds which originate from a multi-species grass sward (MSS) mix comprising grass (ballintoy and timothy), herb (chicory and plantain), and legume (red clover and white clover) species. Pasture based food production systems are seeking to utilize MSS to minimize applied inputs and increase sustainability. A previously characterized atmospheric Dielectric Barrier Discharge (DBD) reactor which uses air as its input was used for the seed's treatment. Plasma process parameters of treatment time duration and input voltage were optimized against key seed performance parameters. The different plasma-exposed seeds were analyzed for electrolyte leakage, seed vigor index, shoot and root length, fresh-to-dry weight ratio and photosynthetic pigments concentration.

The obtained results were dependent on the seed species and plasma exposure. A significant increase in electrolyte leakage was observed in grass and legume seeds. An increment of up to 43% in seed vigor index was observed in both grass species. Additionally, shoot and root length was improved by 36.97 % and 42.37 % for Ballintoy and red clover respectively. A significant increase in the ratio of fresh to dry weight was observed for all seeds. Moreover, the concentration of photosynthetic pigments chlorophyll a, b, total chlorophyll, and total carotenoids (mg/g) were increased with plasma exposure. These findings indicate that cold plasma treatment can enhance a range of seeds performance with an impact on the sustainability pasture-based food production systems.

# Cold plasma processes and technologies for sustainable agriculture and food processing

**Marianna Roggio (1), Angelica Maria Lanza (2), Pietro Favia (1, 2), Francesco Fracassi (1), Eloisa Sardella (2), Savino Cosmai (2), Danilo Benedetti (2), Fabio Palumbo (2)**

(1) Department of Chemistry, University of Bari
(2) Institute of Nanotechnology

Seeds and plants can be contaminated by pathogens. Contaminations by mycotoxins, secondary metabolites of fungi, can cause acute and chronic toxicity in humans and animals. Toxins of the Fusarium fungi, in particular, are common in cereals and their by-products; different Fusarium species can colonize such crops from the first growth stage and, in certain conditions, they can produce extensive amount of toxins. Pesticides, with all their undesired side effects, are to date the most effective tool available in Agro-Food technology for controlling Fusarium in cereals, to be used during all the critical steps of the vegetative cycle [1]. The "from farm to fork" strategy aims to turn the whole Agro-Food system safer and more eco-compatible by reducing the use of pesticides and fertilizers. In this direction, Low-Temperature Plasma (LTP) processes recently developed for applications in Agriculture and Food technologies are very promising [2]. A homemade AP-DBD plasma reactor powered by an electric generator in the kHz range, equipped with a back-and-forth movable stage, will be used to homogeneously process the seeds and plant propagative materials under the discharges. Two different electrode configurations will be tested, to optimize the AA-AP plasma deposition processes with an aerosol generator (atomizer) of the different active coatings, namely:1) a volume DBD, where the seeds are placed between the electrodes, with the movable stage acting as ground electrode;2) a laminar jet configuration, where the discharge is ignited between two vertical electrodes and it is expanded towards the substrates to be treated. In this case the movable stage acts just as substrate holder. The volume DBD configuration is known to be very effective in increasing the growth rate of the coatings, but it could reveal more sensitive to inhomogeneities due to the different shape and size of the seeds. In the jet configuration, instead, the plasma is scarcely influenced by inhomogeneities of the substrates but the growth rate of the coating should be lower than in the previous case.

# Low-temperature plasma and plasma-activated water as alternative novel technologies for postharvest disease control

**Palma Rosa Rotondo* (1), Caterina Rotolo (1), Domenico Aceto (2), Paolo Francesco Ambrico (2) and Rita Milvia De Miccolis Angelini (1)**

(1) Department of Soil, Plant and Food Sciences, University of Bari Aldo Moro, Bari, Italy
(2) CNR Institute for Plasma Science and Technology (CNR ISTP), c/o Department of Physics, University of Bari Aldo Moro, Bari, Italy

The need for new sustainable technologies to reduce losses and maintain the quality of fruits and vegetables during postharvest storage has grown during recent years. Low-Temperature Plasma (LTP) and Plasma-Activated Water (PAW) are currently proposed as promising tools for inactivation of microbial contaminants, including foodborne pathogens and microorganisms responsible for postharvest decay. The effects of both direct and indirect applications of atmospheric air plasma against major fungal pathogens (Botrytis cinerea, Monilinia fructicola, Fusarium graminearum, Aspergillus carbonarius, Penicillium italicum, Penicillium digitatum, Alternaria alternata) and contaminant bacteria (e.g., Bacillus subtilis) were investigated in in-vitro assays using different treatment conditions and exposure times. Three different plasma sources, i.e., Surface Dielectric Barrier Discharge (SDBD), Atmospheric Pressure Plasma Jet (APPJ), and Volume Dielectric Barrier Discharge (VDBD), were applied. Albino mutants of Botrytis cinerea and Aspergillus carbonarius were used to explore the protective role of fungal melanin on sensitivity to plasma exposure, with mutants showing higher sensitivity to treatments compared to the melanized wild-type strains. As expected, inhibitory effects increased with higher exposure times. The complete spore inactivation was obtained after a few seconds (VDBD) or minutes (SDBD and APPJ) of exposure. Major structural damages to the conidia surface after plasma treatment were assessed by Scanning Electron Microscopy (SEM) analysis. An early etching and later perforation of cell walls up to complete cell disruption was observed. A decrease in viability of conidia and an increase in their membrane permeability was assessed by fluorescence-based assays. Differences in the response to plasma among species that could be related to the fungal cell structure and composition were observed, with the strongly melanized conidia of A. carbonarius and A. alternata showing the lowest sensitivity to the treatments. Antibacterial and antifungal activities of PAW having different contents in reactive species (hydrogen peroxide, nitrite and nitrate), pH, and ORP under different treatment conditions (i.e., plasma source, exposure time, gas flow) were evaluated. Results revealed a close correlation between chemical properties of PAW and inhibition rates for bacteria and fungi. Furthermore, inhibitory effect of PAW against all the tested microbial species was proved

stable, with a persistence of at least 30 min after water activation. The efficacy of PAW was also tested on fruits of Citrus sinensis cv. Fukumoto artificially inoculated with P. italicum with a total inhibition of the infection development and symptoms appearance recorded on treated fruit. Experiments on cherry fruits artificially inoculated with B. cinerea and M. fructicola and exposed to SDBD air plasma demonstrated that the application of cold plasma on fruits may significantly extend their shelf life by direct inactivation of fungi and possible activation of plant defense responses.

# Real scale treatment of indoor air by cold atmospheric plasma and photocatalysis

**T. Vazquez (1), D. Wiedermann (2), J. Babic (2), Z. Machala (1)**

(1) Faculty of Mathematics, Physics, and Informatics, Comenius University Bratislava, Slovakia
(2) IQ Capital s.r.o., Banská Bystrica, Slovakia

Indoor air pollution is an important health problem as it can be the cause of more than millions of deaths each year [1]. Exposure to harmful compounds contained in air (chemical pollutants, bacteria, pathogens, cigarette smoke, etc.) is higher indoors thanoutdoorsr and might be responsible for respiratory diseases, cardiovascular diseases, and cancer. Therefore, achieving high indoor air quality would be an important step forward for public health.

Traditional ways to treat polluted indoor air is the use of filters. Filters just trap the pollutants (with a variable efficiency) and need to be replaced. In this study, we used cold atmospheric plasma and photocatalysis for the treatment of indoor air at large gas flow rates (>100 L/min). The main advantage of using these technologies is the capability to destroy pollutants. In addition, cold atmospheric plasma and photocatalysis have been shown to be efficient for the decomposition of a wide range of pollutants, and they have also recently proved to be effective for inactivation of viruses such as SARS-CoV-2 [2, 3].

We designed an air decontamination device that combines a surface Dielectric Barrier Discharge (DBD) for plasma generation, and a $TiO_2$ coating which is activated by UV-A LEDs. The main goal of this work is to decompose chemical pollutants to form $CO_2$ and $H_2O$. The tested pollutants were formaldehyde, acetone and acetaldehyde, as representative indoor volatile organic compounds (VOCs) pollutants.

The overall efficacy of the device appeared to be promising, given the very short residence time of the pollutant in the reactor (single-pass method and a large gas flow). We also monitored the concentration of ozone generated by the DBD, which is a strong oxidant of the pollutants but is well decomposed by the photocatalytic process to prevent its outflow from the device. Electrical parameters of the DBD are key components to find the best compromise between the species produced by the plasma, the interaction with the photocatalysis process, and the overall efficiency of the device.

This work was supported by Slovak Research and Development Agency APVV-17-0382, and APVV-20-0566, and a postdoctoral support of Comenius University Bratislava.

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# Low-pressure plasma irradiation for water disinfection

**Mark Zver* (1, 2), David Dobnik (3), Rok Zaplotnik (1), Miran Mozetič (1), Arijana Filipić (3), Gregor Primc (1)**

(1) Department of Surface Engineering, Jozef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia
(2) Jozef Stefan Post-Graduate School, Jamova cesta 39, 1000 Ljubljana, Slovenia
(3) National institute of Biology, Večna pot 111, 1000 Ljubljana, Slovenia

Viruses are ubiquitous and persistent contaminants in our environment. As some of them cause severe health problems, we need to remove them from any materials and mediums we come into contact with. Water serves as a transmission medium, through which viruses can spread to their host, causing an infection. Inactivating viruses in water is usually the last step in water treatment setups and entails using chemical disinfectants, filtration techniques, oxidants, or UV radiation, which are either environmentally problematic, difficult to maintain, or inefficient. Low-pressure plasma radiation is a unique source of highly energetic vacuum ultraviolet (VUV) photons that can disrupt the viral structure, thus inactivating viruses. In addition, they interact with water molecules and break them apart, producing highly oxidative compounds such as OH radicals which also have antiviral properties. However, it is difficult to generate low-pressure plasma in the presence of liquid water. Additionally, vacuum ultraviolet radiation is completely absorbed by oxygen in the air, precluding the application of the VUV radiation to liquid samples. To treat water with low-pressure plasma, we have constructed a hermetically sealed chamber with an $MgF_2$ window facing the plasma source. Within this chamber, we enclosed a water solution of MS2 bacteriophage in a nitrogen atmosphere to allow for VUV radiation to reach the sample. The solution was treated with low-pressure (500 Pa) hydrogen plasma radiation, ignited with 50 W, using a DC-pulsed generator. Plasma radiation alone was sufficient to inactivate 99% of viruses within 5 minutes of treatment, and after 10 minutes, no viruses were detected in the sample. The reaction between OH radicals and terephthalic acid produces hydroxy-terephthalate (HTA), confirming the generation of OH radicals, which may be responsible for the observed viral inactivation.

# Plasma-based synthesis of titania nanostructures

**Jan Hanuš (1), Dujearic-Stephane Kouao (2), Katarzyna Ssiuzdak (2), Radka Šimerova (3), Tereza Košutova (1), Vítězslav Stranak (3), Petr Sezemsky (1), Katarzyna Grochowska (2) and Ondřej Kylian (1)**

(1) Charles University, Faculty of Mathematics and Physics, V Holešovičkách 2, Praha 8, 18000, Czechia
(2) The Institute of Fluid-Flow Machinery, Polish Academy of Sciences, Centre for Plasma and Laser Engineering, Fiszera 14, 80-231 Gdańsk, Poland
(3) University of South Bohemia in České Budějovice, Faculty of Science, Branišovská 1760, České Budějovice, 37005, Czechia

Titania nanostructures find numerous applications in gas sensing, biosensing, fabrication of self-cleaning surfaces, etc. Most of the applications rely on photocatalytic properties of the $TiO_2$ in anatase crystalline phase. Two different approaches are well established for $TiO_2$ deposition by low-pressure non-equilibrium plasma: i) sputtering either from Ti or $TiO_2$ target or ii) PECVD from titanium isopropoxide. In both cases, a reactive mixture of Ar and $O_2$ should be used and the substrate temperature has to be higher than 100 °C. Unfortunately, such deposited $TiO_2$ coatings are usually smooth without any nano- or micro-architecture.

The structured titania coatings can be prepared by post-oxidation of the plasma-deposited structured Ti films, e.g., films prepared by glancing angle deposition at a pressure lower than 0.1 Pa. Another option is to combine the deposition of Ti film with Ti nanoparticles (NPs). The structure of the coating can be easily controlled by changing the ratio of the deposited NPs and thin film. However, thermal annealing at the temperature range of 400 °C to 550 °C is typically needed to convert the metallic Ti into the $TiO_2$ in the anatase crystal structure. Therefore, such a process is not applicable to heat-sensitive substrates. Moreover, the annealing times can take several hours to reach fully oxidized Ti films with several hundreds of nm thicknesses. In addition, the annealing can also induce the formation of different $TiO_2$ crystallographic phases (rutile and brookite), which may compromise the desired functionality of the resulting materials.

A different Ti to $TiO_2$ conversion approach relies on the anodization of smooth compact plasma-deposited Ti film. Depending on the anodization conditions, closely packed (‘aligned’) or self-standing (‘spaced’) titania nanotubes (TNT) can be prepared. The annealing process is also in this case necessary to ensure the full crystallization of the TNT into the anatase form. The electrochemical and optical properties of the TNT can be tuned by doping the Ti film before the anodization.

The properties of different nanostructured $TiO_2$ coatings will be compared in this study. The effect of the doping of the Ti film by Ag and Cu on the formation of TNT will also be discussed.

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# Nitrogen fixation in sub-micrometer-size water aerosol using micro-hollow surface DBD reactor

**V. Jirásek, T. Homola, J. Fujera, V. Prukner, and M.Šimek**

Institute of Plasma Physics, Czech Academy of Sciences

Ammonia and nitrogen fertilizers are essential components for plant growth. Since the 1960s, the application of various fertilizers has increased more than five-fold, and the ammonia currently produced using the Haber–Bosh process has a massive carbon footprint owing to the production of hydrogen, an ammonia precursor, from fossil fuels. Furthermore, because fossil fuel supplies have become geopolitically destabilized, alternative methods for producing ammonia and fixing nitrogen in water are becoming extremely important for sustainably producing fertilizers and, thus, preventing global food crises. Non-thermal plasma reactors, which enable electrical discharges to be generated in various gases and both liquid and gaseous water, have attracted considerable attention as an alternative method for producing ammonia and fixing nitrogen. Here we used a multihollow surface dielectric barrier discharge (MSDBD) to generate plasma in synthetic air and nitrogen containing admixtures of very fine (< 300 nm) water aerosols. The combination of MSDBD plasma with water aerosols enabled fast solvation of gaseous plasma products in water and production of plasma-activated water (PAW) with the admixture of ammonia. The plasma interaction with the water aerosols was studied using optical emission spectroscopy and a scanning mobility particle sizer to provide information about the size and distribution of the water particles entering and exiting the plasma reactor. The gas exiting the plasma reactor was analyzed using Fourier-transform infrared spectroscopy, and the PAW collected in an ice-cooled vessel was analyzed for nitrogen products and $H_2O_2$. The MSDBD shows promise as a catalyst- and H2-free method for fixing nitrogen in water. Moreover, because MSDBD consumes very little energy (<5 W) and the plasma unit is simple to construct, the proposed method for producing PAW is a promising alternative toward building a decentralized sustainable economy.

# Plasma assisted modification of colloidal nanoparticles

**Kinga Kutasi *(1), Zsolt Tóth (2)**

(1) Wigner Research Centre for Physics, Institute for Solid State Physics and Optics, Budapest, Hungary
(2) Department of Medical Physics and Informatics, University of Szeged, Szeged, Hungary

A new methodology is tested for the modification of the colloidal nanoparticles. The method relies on the use of reactive oxygen and nitrogen species (RONS) enriched liquids. The reactive species are deposited into the liquid through the interaction of an atmospheric pressure surface-wave microwave discharge with the liquid [1]. During plasma-liquid interaction high reduction potential metal powder is added to the liquid in order to compensate for the plasma-induced acidification, and thus ensure a long lifetime for the RONS [2]. The nanoparticle (NP) colloids are created by laser ablation of solid target in liquid (LAL). NPs are created both in deionized and in RONS-enriched water, respectively. It is shown, that both the structure and the oxidative state of NPs are modified when using RONS-enriched liquids during LAL.

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# Analysis of reactive sputtering in DC magnetron sputtered and high target utilization sputtered TiNbVTaZrHf-xN coatings

**F. Lofaj* (1), L. Kvetková (1), P. Hviščová (1), M. Kabátová (1), T. Roch (2), V. Girman (1, 3)**

(1) Institute of Materials Research of SAS, Watsonova 47, 04001 Košice, Slovakia
(2) Faculty of Physics, Mathematics and Informatics, Comenius University in Bratislava, Mlynská dolina F1, 84248 Bratislava, Slovakia
(3) Faculty of Science, Pavol Jozef Šafárik University in Košice, Park Angelinum, 04154 Košice, Slovakia

Multicomponent transition metal (TM = Ti, Nb, V, Ta, Zr, Hf) nitrides forming homogeneous solid solutions analogous to high entropy metal sub-lattice stabilized ceramics became attractive due to their high thermal, mechanical and corrosion properties. They are usually produced by reactive deposition involving reactive arc and/or reactive sputtering. All the above-mentioned TMs are strong nitride formers, therefore, strong target poisoning and related hysteresis behavior can be expected during reactive deposition. The aim of the current work was therefore, the investigation of the similarities and differences in reactive sputtering of TiNbVTaZrHf-xN (x – flow of nitrogen) coatings prepared by High Target Utilization Sputtering (HiTUS) and reference DC magnetron sputtering (DCMS) The investigations were focused on composite target poisoning, pressure changes in the plasma and hysteresis behavior in both techniques, and the discussion of the results within the commonly accepted Berg's model of reactive sputtering.

Pressure changes during nitrogen increase/decrease cycle revealed three different regimes nitrogen consumption during nitride formation but similar both in DCMS and HiTUS of composite target sputtering. Although target poisoning occurred regardless of the sputtering technique, the hysteresis behavior was within the scatter of measurement error. Thus, the current cases correspond to a specific situation of reactive sputtering without hysteresis.

The possible mechanisms of reactive plasma processes with suppressed hysteresis were analyzed within Berg's model of reactive sputtering controlled by reactive gas supply. Based on the analysis of pressure changes in the plasma, phenomenological model based on continuous target poisoning for different regimes of nitrogen consumption was proposed. It was corroborated by the evolution of deposition rates, stoichiometry and mechanical properties of DCMS and HiTUS TiNbVTaZrHf-xN coatings.

# Various plasma-liquid discharge regimes determine the plasma-activated water properties and applications

**Zdenko Machala (1), Mostafa E. Hassan (1, 2), Pankaj Pareek (1), Saeed Kooshki (1), Oleksandr Galmiz (1), Patrik Štípala (1), Karol Hensel (1), Mario Janda (1)**

(1) Faculty of Mathematics, Physics, and Informatics, Comenius University Bratislava, Slovakia
(2) now with Institut Prime (CNRS UPR 3346-Université de Poitiers-ENSMA), Chasseneuil Futuroscope, France

Atmospheric air plasma produces a cocktail of reactive oxygen and nitrogen species (RONS) with various lifetimes, reactivities, and functions. The plasma chemistry is initiated by elementary processes of ionization, excitation, and dissociation; thus it leads to the formation of radicals and other RONS, and induces their mutual reactions. Specific composition of plasma gaseous RONS depends on the plasma discharge type and its power and geometry, the feed gas, its flow rate, the presence of water, and other environmental parameters. Besides the long-lived gaseous RONS such as ozone or nitrogen oxides, plasma also creates short-lived ones (e.g. hydroxyl OH•, atomic oxygen O•, superoxide $O_2^{-}$• radicals, or molecular singlet delta oxygen $^1O_2$) that strongly influence the plasma reactivity and its effects, although their diagnostics are challenging. Once plasma interacts with a liquid at the gas-liquid boundary, or in hybrid gas-liquid aerosol or bubble systems, gaseous RONS are transported into the liquid and the evaporation strongly influences the plasma processes. The transport of RONS to the liquid phase through the plasma–liquid interface can be significantly enhanced by increasing the interface area, e.g. by converting bulk water to aerosol microdroplets [1]. The solubility of various plasma RONS does not perfectly match with the equilibrium of Henry's law. We verified the applicability of Henry's law coefficients for plasma–liquid interaction with bulk water vs. charged electrosprayed vs. non-charged aerosols [2]. In the liquid, the plasma-formed, as well as the new ionic RONS diffuse and undergo further reactions. They are crucial when the plasma-treated (activated) liquid interacts e.g. with organic pollutants, biomolecules, live cells, tissues, or plant seeds.

We compare various air plasma discharges interacting with water solutions (DC and ns-pulsed driven streamer corona and transient spark, atmospheric glow discharge, surface, and volume DBDs), by analysing their RONS. While low power streamers and DBDs in air produce dominantly ozone, higher power air discharges generate more OH•, hydrogen peroxide $H_2O_2$, $NO_x$, and nitric/nitrous acids. However, due to various gas-liquid transport rates, even ozone-dominated plasma will not generate high liquid ozone concentrations but rather $H_2O_2$ and some

$NO_3^-$, which can be still efficient against microorganisms or cancer cells. On the contrary, $NO_x^-$dominated plasma makes RNS-dominated plasma-activated water, which are strongly antimicrobial if both $H_2O_2$ and nitrites $NO_2^-$ are present and form peroxynitrites. RNS-dominated PAW can be also used as a $NO_3^-$-rich fertilizer and plant growth promoter in sustainable agriculture.

The selection of the discharge regime and its operational environmental parameters strongly influence the properties of the plasma-activated water and determines its suitability for specific applications. This fundamental knowledge can lead to optimized designs of plasma–water interaction systems for multiple applications.

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# Plasma technologies in view of Industry 4.0

**Miran Mozetič**

Department of Surface Engineering, Jožef Stefan Institute, Ljubljana, Slovenia

Plasma technologies are widely used for surface modifications of solid materials on the industrial scale. The basic principle is the establishment of gaseous plasma with desired properties and allowing the reactive plasma species (ions, radicals, and radiation) to interact with the surfaces. The surface finish obviously depends on the fluxes and fluences of selected plasma species. Despite this obvious fact, many currently used plasma reactors don't allow for measuring the fluxes, let alone adjusting the fluxes according to the evolution of the surface properties. The adjustable parameters of plasma reactors are usually the gas pressure and/or the flow of gases, the discharge power, and the treatment time. Even scientific literature on plasma-surface interaction rarely reports the fluxes of plasma species. The adaptation of plasma reactors towards the demands of Industry 4.0 will be presented and illustrated for both plasma activation of organic materials and plasma-enhanced chemical vapor deposition of thin films. The inclusion of sensors useful for measuring the fluxes of reactive plasma species is essential for making the plasma reactors smart, i.e., self-adjusting according to the evolution of surface properties.

# Integrated numerical modelling of cell fate determination in response to plasma-induced reactive species

**Tomoyuki Murakami**

Faculty of Science and Technology, Seikei University, Tokyo, Japan

The aim of this numerical study is to quantitatively trace the trajectory of cold atmospheric plasma (CAP)-induced reactive oxygen and nitrogen species (RONS) from a plasma source to biological cells and identify the biologically important species in cell fate determination. The present numerical model conceptually integrates the following four domains. (1) The plasma discharge properties and gas-phase chemistry in the core region of a CAP source, which are described by a one-dimensional model. (2) The gas-phase chemistry in the afterglow plasma released in the humid ambient air, which is simulated by a two-dimensional fluid-dynamical model. (3) The aqueous chemistry of plasma-activated air-saturated water or saline solution simulated by a one-dimensional liquid-phase reaction-diffusion model. (4) A zero-dimensional intracellular biochemical reaction model quantifies the influence of CAP-induced RONS on the determination of the cell death/survival. The newly developed interdisciplinary model should be a powerful tool to understand the crucial "multiphase pathway" systematically and help us to identify the intracellular mechanism correlating with CAP effects.

# Breakdown and volt-ampere characteristics of low-current discharges in water vapour

**Zoran Lj. Petrović (1, 2), Jelena Marjanović (3), Gordana Malović (3) and Dragana Marić (3)**

(1) Serbian Academy for Sciences and Arts, Knez Mihailova 35, 11001 Belgrade, Serbia
(2) School of Engineering, Ulster University, Jordanstown, County Antrim BT37 0QB, United Kingdom
(3) Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080, Belgrade, Serbia

Water vapour is necessarily a constituent of living organisms and often the primary environment for growth and reproduction. In addition, it is always present in the air but in interfaces to liquids its density varies and so do the abundances of the related reactive species. Thus, studies of the breakdown in water vapour are of interest for a broad range of plasma applications and novel fundamental issues. Measurements of the breakdown voltage provide information on the dielectric properties of the vapour and its mixtures, ionization coefficient and have a basic albeit simplified relationship to the secondary electron yield processes. More profound understanding of the secondary yields and also of the basis for normalizing the cross-section sets may be obtained from the low current limit of the Volt-Ampere characteristics. However, in case of water vapour it proved difficult to extend those measurements due to high negative differential resistance resulting in relaxation oscillations. As our measurement of the breakdown voltage consists of measurements at low currents extrapolated to the zero current, we had to develop a procedure to obtain the Volt-Ampere characteristics even in case of such oscillations and the results will be presented in this review. In addition, observing spatial emission profiles allows us to determine the effective electron density growth coefficient that may be reduced to the ionization coefficient in the high normalized field limit. The same data provide observation of the growth of the fast neutral excitation presumably due to fast hydrogen atoms released in the discharge. Measurements were made at pd = 1.1 Torr cm (p-pressure, d-interelectrode distance). For the range of conditions where we could obtain data with both a stable dc discharge and an oscillating discharge procedure provided a very good consistency between the two sets of results.

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# Low-temperature plasma processing modulation using external means for electrocatalytic electrode surface manipulation

**Bo Ouyang and Rajdeep Singh Rawat**

National Institute of Education, Nanyang Technological University, Singapore

Due to enormously high prices and low reserves of Pt which has best electrochemical hydrogen production capabilities, transition metal nitrides (TMNs) have been explored actively for non-precious metal-based electrocatalytic $H_2$ production [1, 2]. Several studies on have confirmed TMN-based nano-frameworks to be efficient HER electrocatalysts, but complicated and energy intensive thermal nitridation fabrication process inevitably deteriorates TMNs nanostructures leading to the restricted and inefficient application in hydrogen production [3, 4]. Compared to thermal nitridation, low plasma nitridation serves as a favorable alternative for nanostructured TMN synthesis but the apparent surface heating effect during plasma treatment inevitably causes the thermally stabilized nitride formation resulting in deterioration of hydrogen production capability of the synthesized electrode. We have developed different strategies to control the electrode surface temperature during low temperature plasma treatment to achieve the desired nano-framework on the plasma treated TMN electrode surface that delivers exceptional catalytic performance. Details of plasma parameters with and without auxiliary surface temperature modulations and electrochemical performance of the low temperature plasma synthesized TMNs will be discussed during the presentation.

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# Regeneration of clinoptilolite saturated with ciprofloxacin by using atmospheric pressure plasma

**Nikola Škoro (1), Barbara Kalebić (2), Janez Kovač (3), Nevenka Rajić (2)**

(1) Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia
(2) Faculty of Technology and Metallurgy, University of Belgrade, Karnegijeva 4, 11120 Belgrade, Serbia
(3) Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia

Water pollution by organic micropollutants (OMPs) has increased alarmingly worldwide in recent years. Antibiotics are also considered as OMP. Their presence in water bodies has harmful effects on environment and humans. Usually antibiotics cannot be efficiently removed from water by conventional water treatment processes and are present even in drinking water.

Adsorption has been found as a promising method for achieving sufficient removal efficiency of OMPs including organic dyes, pesticides and pharmaceuticals. Natural zeolite - clinoptilolite (CLI) is one of the widely available, efficient and low-cost zeolites. It has been found very efficient in adsorption of various types of inorganics, organics as well as OMPs.

When applying adsorption in water treatment, very important issue is the regeneration of the adsorbent. Regeneration of the spent zeolite-based adsorbents are usually based on thermal and/or chemical methods. However, these two methods have numerous disadvantages when zeolite-based adsorbent is used for organics removal (blocking of zeolite pore system with coke during calcination, loss of crystallinity during acid application, incomplete regeneration, etc).

In this study, it was tested for the first time an atmospheric pressure plasma for regeneration of CLI saturated with antibiotic ciprofloxacin (CIP). CIP is widely applied antibiotic for treatment of both human and animal bacterial infections, and it has been found in wastewater effluents in wide range of concentrations from ng to mg $dm^{-3}$. Extremely high concentration of up to 50 mg $dm^{-3}$ has been found near drug manufacturing plants.

In previous studies we have found a high adsorption affinity of CLI towards CIP, which makes CLI a promising adsorbent for antibiotics removal from water media. To investigate the CLI reusability, the spent CLI was treated by using a surface dielectric barrier discharge (DBD) source operating in air with one electrode powered by continuous 50 Hz high-voltage signal. Regeneration of the adsorbent efficiency was investigated within five adsorption cycles with plasma treatment as a regeneration step in-between adsorption cycles. Reusability was tested in a solution with the initial CIP concentration of 25 mg $dm^{-3}$ at pH = 5 and within 5 min.

Subsequently, CLI samples before and after the treatment, as well as the saturated CLI was characterized in detail using XRD, Brunauer Emmet Teller (BET) method and XPS. XRD measurements confirmed that plasma treatment did not affect CLI crystallinity while XPS approved decrease of total carbon content with about 10% of carbon residual left on the CLI surface.

Reusability tests demonstrated that the CLI adsorption capacity for CIP could be regenerated by plasma treatments to at least 90% of its initial capacity during the five successive cycles. The CIP removal from CLI surface was attributed to plasma reactive species which decompose CIP at the CLI surface.

Considering obtained results, atmospheric pressure plasma proves to be an innovative method for the regeneration of CLI used in removal of antibiotics from water media.

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# Waterborne virus inactivation using various low-pressure plasma radiation wavelengths and ambient gases

**Mark Zver* (1, 2), David Dobnik (3), Rok Zaplotnik (1), Miran Mozetič (1), Arijana Filipić (3), Gregor Primc (1)**

(1) Department of Surface Engineering, Jožef Stefan Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia
(2) Jožef Stefan post-graduate school, Jamova cesta 39, 1000 Ljubljana, Slovenia
(3) National Institute of Biology, Večna pot 111, 1000 Ljubljana, Slovenia

Waterborne viruses persist and are transmitted to their host through water. As some of them are also pathogenic to humans, they need to be removed from the water we come into contact with, to prevent infection. New water purification technologies are constantly sought for, to reduce costs, improve quality or reduce the environmental impact of water treatment. Owing to its mild operating conditions, negligible environmental burden, and consisting of a plethora of germicidal agents, low-pressure plasma is a viable candidate for the next generation of water treatment processes. In this work we used capacitively coupled low-pressure hydrogen plasma as a source of radiation, which we applied to MS2 virus-inoculated water. Enclosed within a hermetically sealed chamber, the water sample was exposed to plasma radiation through either a $MgF_2$, quartz or borosilicate glass window. Furthermore, we varied the ambient gas within the chamber, with either $N_2$, $O_2$ or air. Along with determining virus inactivation, we recorded the different wavelength spectra reaching the sample and quantified the OH radicals produced, when the window material or ambient gas were changed. We demonstrate that, with correct conditions, low-pressure plasma irradiation alone is capable of inactivating viruses in solution. The inactivation efficiency is determined by the applied wavelength and type of gas present within the chamber. By exposing the sample to plasma radiation through an $MgF_2$ window, and with either oxygen or ambient air present within the chamber, the treatment was able to inactivate over 4 logs of virus within 2.5 minutes.

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# Degradation of micropollutants in secondary wastewater effluent using nonthermal plasma-based AOPs

**Changtao Chen (1, 2, 3), Kristof Demeestere (3), Anton Nikiforov (2), Stijn Van Hulle (1)**

(1) LIWET, Laboratory for Industrial Water and EcoTechnology, Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Campus Kortrijk, Sint-Martens-Latemlaan 2B, B – 8500 Kortrijk, Belgium
(2) RUPT, Research Unit Plasma Technology, Department of Applied Physics, Faculty of Engineering and Architecture, Ghent University, Sint-Pietersnieuwstraat 41, B4, B – 9000 Ghent, Belgium
(3) EnVOC, Research Group Environmental Organic Chemistry and Technology, Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, B – 9000, Ghent, Belgium

Emerging micropollutants (µPs) appearing in water bodies endanger aquatic animals, plants, microorganisms and humans. Most of countries are equipped with very basic wastewater treatment systems to accommodate the populations' needs before discharge into the environment, which may be insufficient to generate treated effluent to be reused in agriculture. The nonthermal plasma-based advanced oxidation process is a promising technology for eliminating µPs in agricultural wastewater but still needs further development in view of full-scale industrial application. A novel cascade reactor design which consists of an ozonation chamber preceding a dielectric barrier discharge (DBD) plasma reactor with a falling water film on an activated carbon textile (Zorflex®) was used to remove a selection of µPs from secondary municipal wastewater effluent. Compare to the previous plasma reactor, molecular oxidants degraded micropollutants again in an ozonation chamber in this study, and the utilization of different reactive oxygen species (ROS) was improved. A gas flow rate of 0.4 standard liter per minute (SLM), a water flow rate of 100 mL $min^{-1}$, and a discharge power of 25 W are identified as the optimal plasma reactor parameters, and the µP degradation efficiency and electrical energy per order value (EE/O) are 84-98% and 2.4-5.3 $kW/m^3$, respectively. The presence of ROS during plasma treatment was determined in view of the µPs removal mechanisms. The degradation of diuron (DIU), bisphenol A (BPA) and 2-n-octyl-4-isothiazolin-3-one (OIT) was mainly performed in ozonation chamber, while the degradation of atrazine (ATZ), alachlor (ALA) and primidone (PRD) occurred in entire cascade system. The ROS not only degrade the µPs, but also remove nitrite (90.5%), nitrate (69.6%), ammonium (39.6%) and bulk organics (11.4%). This study provides insights and optimal settings for an energy-efficient removal of µPs from secondary effluent using both free radicals and molecular oxidants generated by the plasma in view of full-scale application.

# Underwater plasma initiation

**T. A. Field, F. Hassan, K. Shojaa, D. McCartney, A. Murphy, M. Karim, L. Asimakoulas**

Centre for Light-Mater Interactions, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, N. Ireland, UK

The initiation of plasmas with submerged electrodes has been investigated. Time-resolved shadowgraph and spectroscopic investigation has been made. The time that it takes to form a plasma is well-modelled by a very simple calculation based on a gross set of assumptions. Generally two phases are observed, a heating and then discharge phase. This is similar for ionic solutions and deionised water. Emission spectra show marked variation over timescales of microseconds, which may give clues to the evolution of the discharge.

# Synthesis of molybdenum doped diamond-like carbon films by magnetron sputtering

**H. Zhairabany (1), L. Marcinauskas* (1, 2), V. Dovydaitis (1), E. Gnecco (3)**

(1) Kaunas University of Technology, Department of Physics, Studentų str. 50, Kaunas, Lithuania
(2) Lithuanian Energy Institute, Plasma Processing Laboratory, Breslaujos str. 3, Kaunas, Lithuania
(3) M. Smoluchowski Institute of Physics, Jagiellonian University, ul. Lojasiewicza 11, Krakow, Poland

Various metals such as Mo, Ag, Ti, Cr, Ag, etc. are used as dopants for the diamond-like carbon (DLC) films. Each dopant has unique role in modifying the film structure and as consequence enhancing a desirable property of DLC thin films. It was demonstrated that the Mo-doped DLC films has demonstrated better tribological properties and enhanced mechanical characteristics. The objective of this work was to deposit and characterize the microstructure and tribological properties of DLC films with various Mo content, focusing on the nanoscale tribological properties.

Molybdenum-doped amorphous diamond-like carbon thin films (Mo-DLC) were formed on Si (100) substrates by direct current magnetron sputtering. The graphite and the molybdenum cathodes were used. The arc currents were fixed at 1.0 A and 0.25 A, and the temperature of formation was changed. The Mo content were changed by increasing the opening of a shield mounted above the molybdenum target from 4 mm to 32 mm. The elemental composition, surface morphology, structure, nanohardness and friction forces of the Mo-DLC films were investigated by energy dispersive X-ray spectroscopy (EDS), atomic force microscopy (multimode 8 Bruker), MTS-Agilent G200 nanoindenter and Raman spectroscopy. The EDS results indicated that the Mo content increased with the opening of the shield above the Mo target. Additionally, the Raman spectra of the films indicated that the $sp^2$ carbon sites fraction increased, and the graphitization was induced with the increase of the formation temperature. The friction coefficient of the Mo-doped DLC films depended on the structure and composition of the films. The nanohardness and the Young’s modulus of the Mo-DLC films was enhanced with addition of low amount (up to 6 at.%) of Mo.

# Creation of reactive species by two atmospheric pressure plasma sources while treating water for biomedical applications

**Neda Babucić*, Olivera Jovanović, Nikola Škoro and Nevena Puač**

Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia

Low-temperature plasma (LTP) has gained significant attention due to its versatile applications in water decontamination, agriculture, and biomedical fields. One of the key challenges in plasma-water interaction is to enhance the flux of reactive species from plasma to liquid. Aerosols, in the form of micrometer-scale droplets, immersed in plasma have been proposed as a strategy to increase the contact area and potentially enhance rates of chemical interaction between plasma and liquid.

Recent research has focused on the development of plasma sources operating at atmospheric pressure in contact with liquid samples, driven by biomedical applications such as wound healing, cancer treatment, deactivation of bacteria and viruses, and sterilization. Plasma Activated Liquids (PALs) have been widely used in numerous successful experiments, but questions remain regarding the mechanisms governing the interaction between plasma and liquid, including the production of various chemical species.

In this work, we utilized atmospheric pressure non-equilibrium plasma sources for the treatment of distilled water and the production of PALs. The first device was a plasma jet with pin-electrode configuration, operated in kHz frequency regime, and the second was microwave launcher that operated at 2.45GHz. In all experiments, Ar was used as a working gas with varying flow from 1 to 3 slm. Optical emission spectroscopy and plasma imaging provided information about the excised species and the point where the concentration of reactive oxygen and nitrogen species (RONS) was largest. Diagnostics of liquid samples were performed to assess the effectiveness of plasma treatment, including measurements of conductivity, pH, temperature, and the amount of deposited RONS.

Overall, this work contributes to a better understanding of different plasma sources and their potential for effective usage in biomedical applications, through changing plasma parameters and treatment conditions.

# Air surface dielectric barrier discharge as a tool for decontamination of synthetic seeds

**Nevena Puač (1), Slađana Jevremović (2), Suzana Živković (2) and Nikola Škoro (1)**

(1) Institute of Physics-National Institute of Republic of Serbia, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia
(2) Institute for Biological Research "Siniša Stanković"-National Institute of Republic of Serbia, University of Belgrade, Bul. despota Stefana 142, 11060 Belgrade, Serbia

The atmospheric pressure plasmas with the rich plasma chemistry are widely used for treatment of seeds in order to increase germination percentages or speed up the process of the plant development [1]. The reactive oxygen and nitrogen species (RONS) interact with the seed coat and trigger various responses like increased water uptake, changes in the surface of seed's coating or can eliminate the pathogens on the seeds surface. There are many plasma sources used for these purposes. They vary in geometry, type of applied voltage, frequency, feeding gas etc. This enables large variety of applications in plasma agriculture field, but also complicates the comparison of the results. In that sense, it is of outmost importance to characterize plasma sources in detail.

Here we will present the diagnostics and application of the air Surface Dielectric Barrier Discharge (SDBD) source that was used in treatment of Chrysanthemum synthetic seeds [2]. Air SDBD is circular shape with the outer diameter of 90 mm. It consists of the two plan parallel glass plates. The lower glass plate serves as a sample holder while the upper glass plate is covered with conductive strips made of 5 mm wide copper tape. The SDBS was powered with 50 Hz high-voltage (HV) sine signal. We performed detailed electrical characterization and recorded the optical emission spectra (OES) of the SDBD system. Characterization of the device was performed by using spacers with the thickness of 2, 3, 4 and 5 mm.

Synthetic seeds (synseed) are defined as artificially encapsulated somatic embryos or other non-embryogenic vegetative parts of plants that may be used for storage or sowing. Synseed technology represent an efficient alternative technique for propagation and germplasm conservation of plants that produce non-viable seeds or seedless plants. We have treated four different cultivars of Chrysanthemum synseeds by ais SDBD before growing them in aseptic and non-aseptic conditions. This treatment reduced contamination and displayed a high ability to plant conversion ex vitro of clonally identical chrysanthemum plants.

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# The impact of furcellaran sulfation on blood compatibility

**Kateřina Štěpánková* (1), Kadir Ozaltin (1), Radka Gorejová (1, 2) and Marian Lehocky (1, 3)**

(1) Centre of Polymer Systems, University Institute, Tomas Bata University in Zlín, Trida Tomase Bati 5678, 760 01 Zlin, Czech Republic
(2) Department of Physical Chemistry, Faculty of Science, Pavol Jozef Šafárik University in Košice, Moyzesova 11, 041 54, Košice, Slovakia
(3) Faculty of Technology, Tomas Bata University in Zlín, Vavreckova 275, 76001 Zlín, Czech Republic

Biomaterial-based clot formation is the major problem of blood-contacting devices. In order to prevent clot formation, their surfaces must be tailored to improve hemocompatibility. Many synthetic polymers lack chemical bonding sites to immobilize the potential agent that would alter surface characteristics. Therefore, the polyethylene terephthalate (PET) was subjected to air plasma treatment for enhanced hydrophilicity due to the formation of high-density functional groups on the surface. Marine-sourced polysaccharide furcellaran from Furcellaria lumbricalis was employed as an agent to enhance its hemocompatibility. The use of seaweed polysaccharides as a sustainable, non-animal source has gained notoriety in recent years due to their remarkable bioactivities. The anticoagulant, antithrombotic, fibrinolytic, and platelet aggregating effects are primarily attributed to the presence of sulfate groups that play an important role in cell recognition. Chemical modifications, such as sulfation, provide an effective approach to overcoming poor water solubility and improving the bioactivity of natural polysaccharides by altering their structural and conformational properties. Many evidences reported that besides the sulfate pattern, other structural factors such as glycoside linkage configuration, molecular weight and the position of sulfate esters in polysaccharide backbone can significantly enhance bioactivity. These features can be affected by the sulfation method used. Hence four sulfating methods were implemented for furcellaran to obtain sulfate derivates of various sulfation degree and Mw. Structural characterization by FT-IR and XPS showed that oversulfated furcellaran could be successfully synthesized with $SO_3$-pyridine ($SO_3$·Py) complex, chlorosulfonic acid and sulfuric acid with a “coupling” reagent N,N'-Dicyclohexylcarbodiimide. All samples demonstrated an anticoagulant effect by a dose-dependent prolongation of aPPT, TT, and PT and subsequent immobilization of sulfate derives onto PET presented a substantial decrease in platelet adhesion. These data provide new insights into value-added utilization of furcellaran sulfates for blood-contacting biomaterials.