Plasma-liquid interactions, the transport of RONS into liquids, and control of PAW properties

Zdenko Machala *et al.*

FACULTY OF MATHEMATICS, PHYSICS AND INFORMATICS
Comenius University
Bratislava

Division of Environmental Physics,
Comenius University, Bratislava, SLOVAKIA

Ghent University, 22 Sep 2025

ENLIGHT

Acknowledgments

RECOVERY AND RESILIENCE PLAN

EU NextGenerationEU

SLOVAK RESEARCH AND DEVELOPMENT AGENCY

esa

European Space Agency

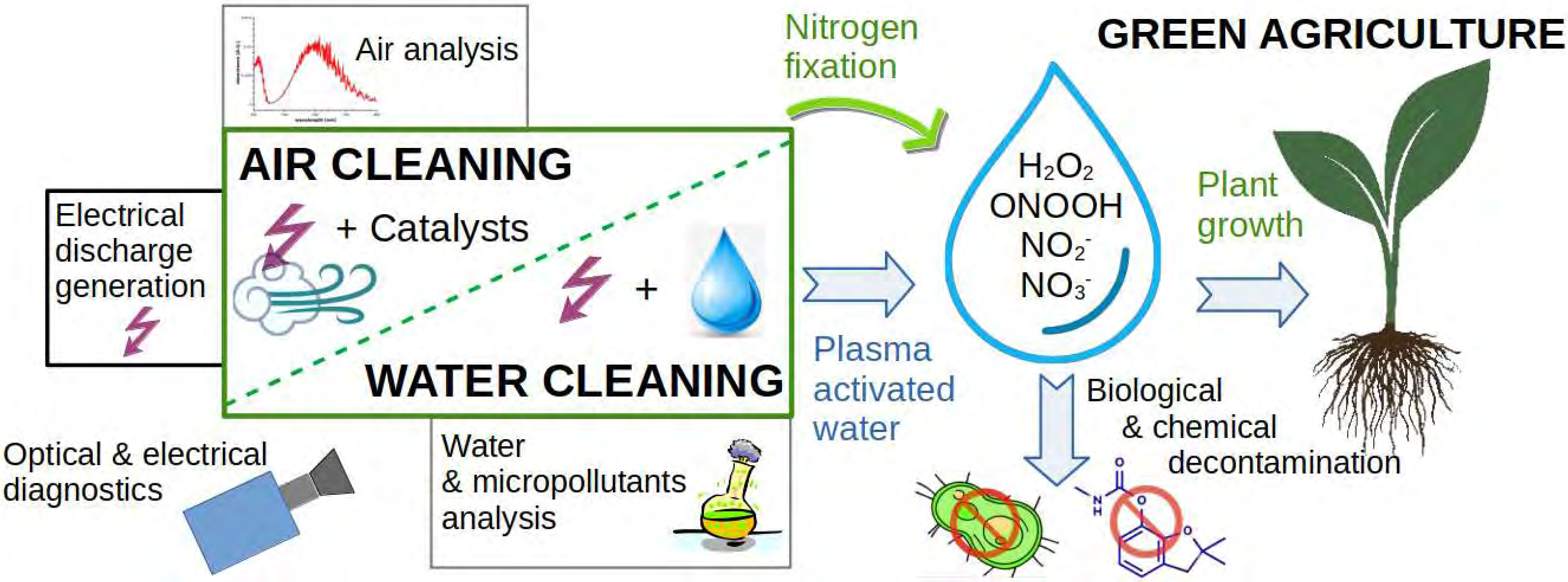
CA19110
Plasma applications for smart and sustainable agriculture

Environmental Physics Division
Faculty of Mathematics, Physics and Informatics,
Comenius University Bratislava, SLOVAKIA

R. Švubová, D. Kostoláni, S. Kyzek, Z. Lukačová, M. Ghulam, B. Šerá, Faculty of Natural Science
H. Gbelcová, B. Konecná, R. Gardlik, P. Celec, Faculty of Medicine, Comenius University Bratislava
+ Slawomir Moritz, Proline Solutions, Austria

Motivation: plasma-liquid environmental applications

(our group research focus)



- **Direct plasma treatments - indirect plasma-activated water (PAW)**

Plasma – water interaction

(A) Discharge directly in liquid (pulsed)

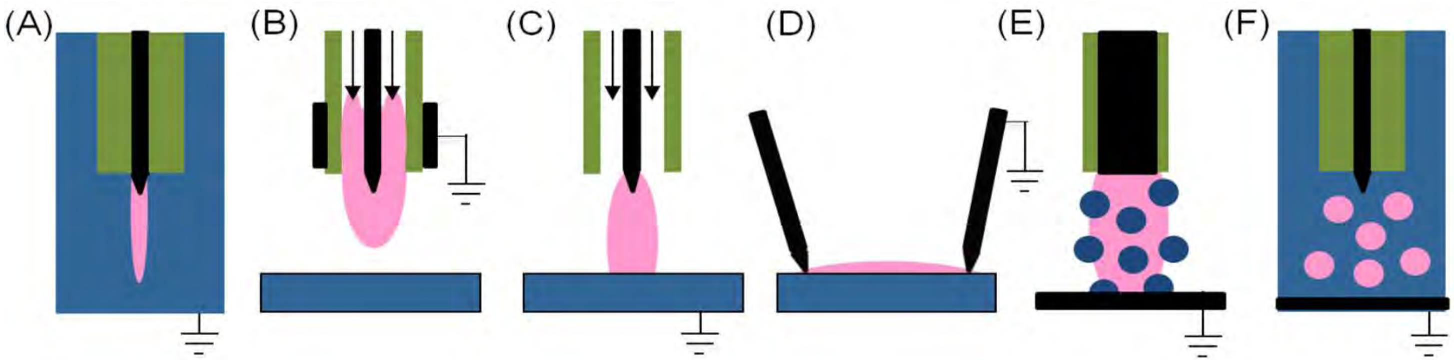
(B) Plasma jet w/o direct contact with liquid

(C) Discharge with liquid electrode

(D) Surface discharge over liquid

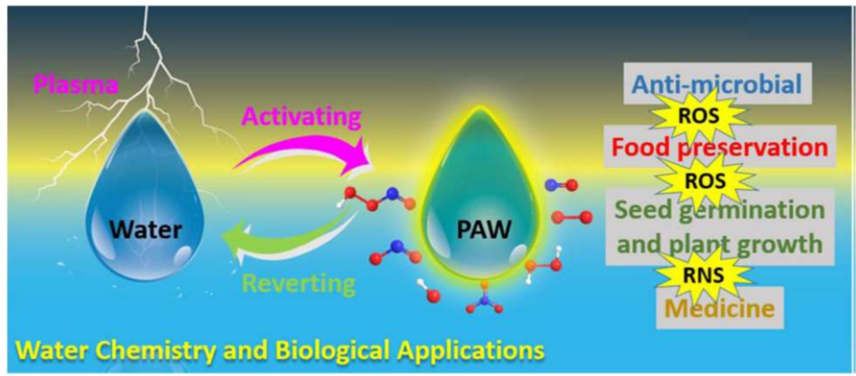
(E) Plasma with dispersed liquid (aerosol)

(F) Discharges in bubbles or foam



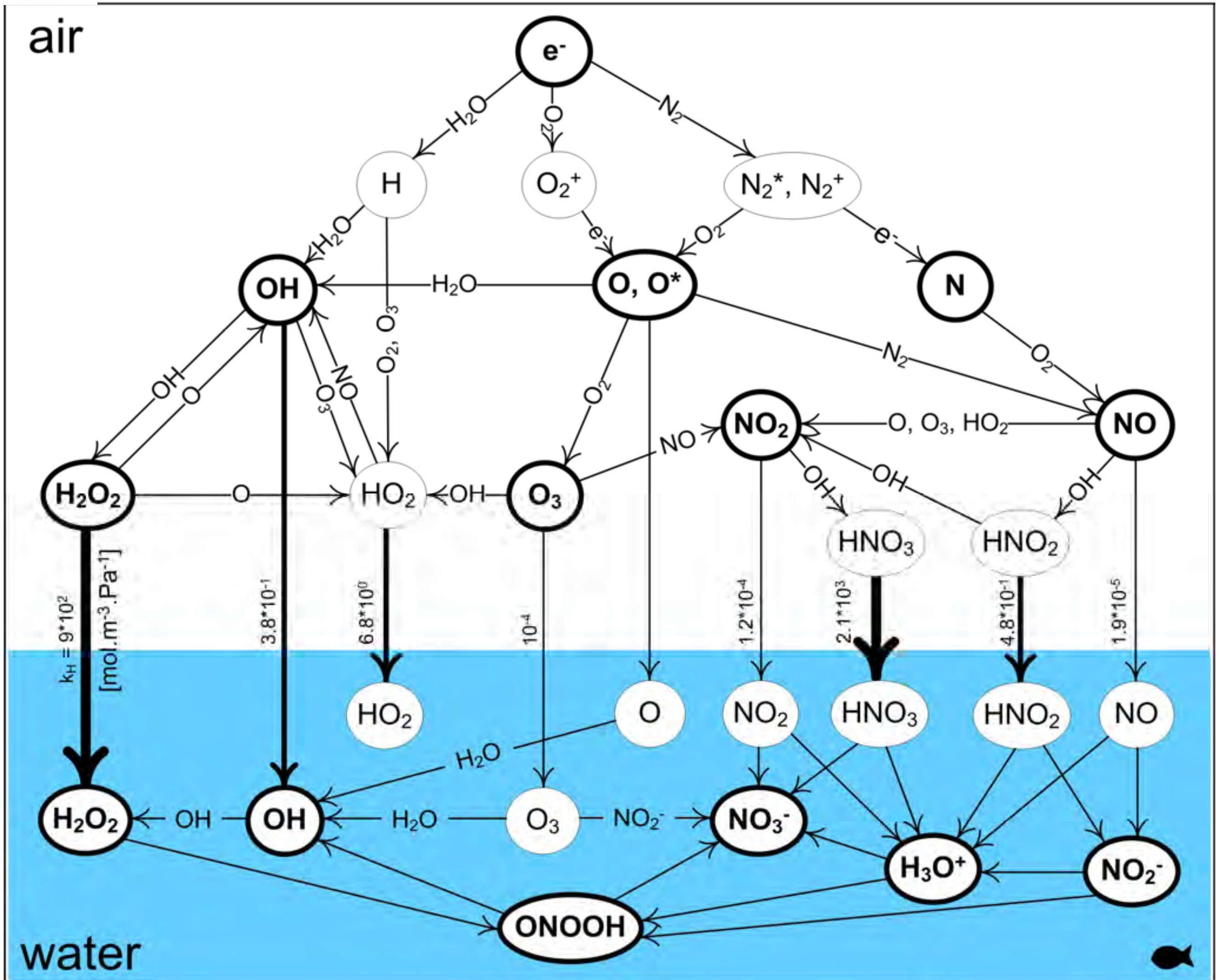
- P. J. Bruggeman et al. Plasma-Liquid Interactions, *Plasma Sources Sci. Technol.* 2016

- **Plasma-activated (treated / processed) water / liquid (PAW / PAL)**
  - Every PAW has different properties depending on the plasma parameters, gas and liquid composition, and exp. conditions



- R. Zhou et al J. Phys. D: Appl. Phys. 2020

Air-water plasma chemistry + transport into water



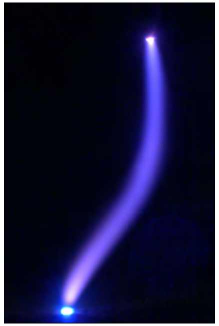
RONS - Reactive Oxygen and Nitrogen Species

- Z. Machala et al., *J. Phys. D,* 2019

Outline

- Air discharges: O_3 vs. NOx mode, plasma chemical processes; effects of power, flow rate, reactor

- Nitrogen fixation and fertilizers

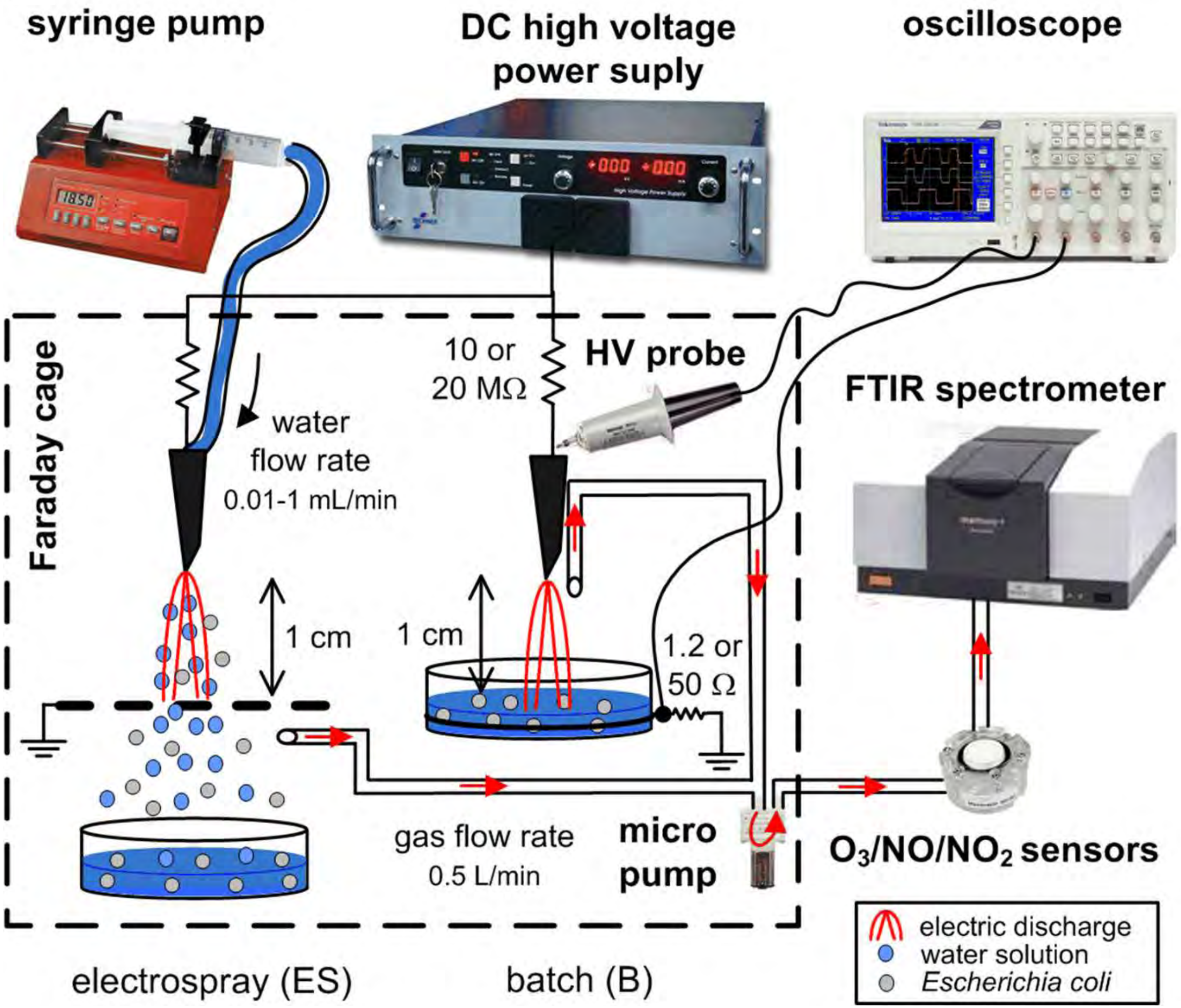


- Transport of plasma reactive oxygen and nitrogen species into water bulk vs. microdroplets

- Air discharges with water: RONS formation in plasma-activated water

- Examples of biomedical/agro applications

Our cold plasma-liquid set-ups



A. Jaworek et al., *J Phys. D* 2019

Gas phase analysis:

NO, NO_2, HNO_2 – electrochemical sensors, FTIR, UV absorption

O_3 – UV absorption (254 nm)

Aqueous phase analysis:

NO_2^-/NO_3^-: Griess reagent → azo product (λ_{max} = 540 nm)

H_2O_2 + Ti^{4+} → $TiO_2.H_2O_2 + 4H^+$ (λ_{max} = 407 nm)

O_3 : indigo blue reagent (λ_{abs} = 600 nm)

$ONOO^-$: H_2DCFDA fluoresc. assay ($\lambda_{ex}/\lambda_{em}$ = 502/521 nm)

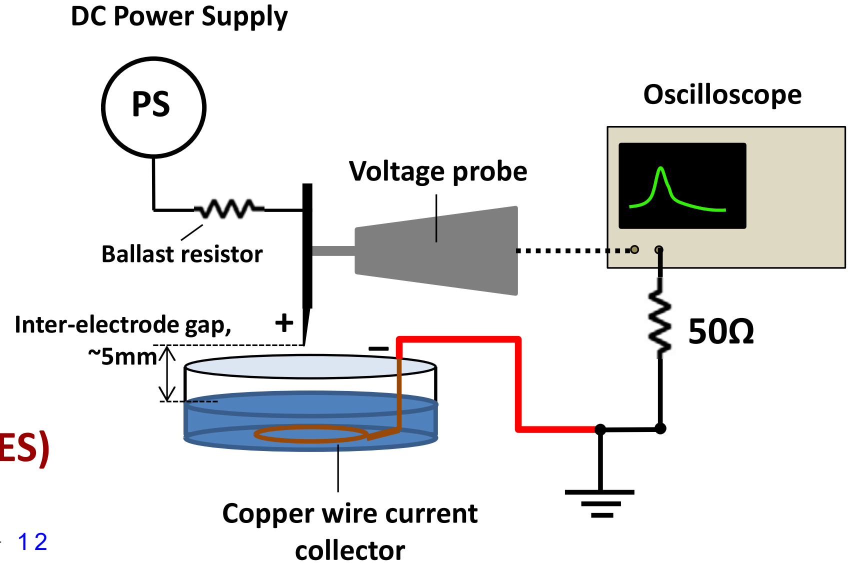
Antibacterial effects:

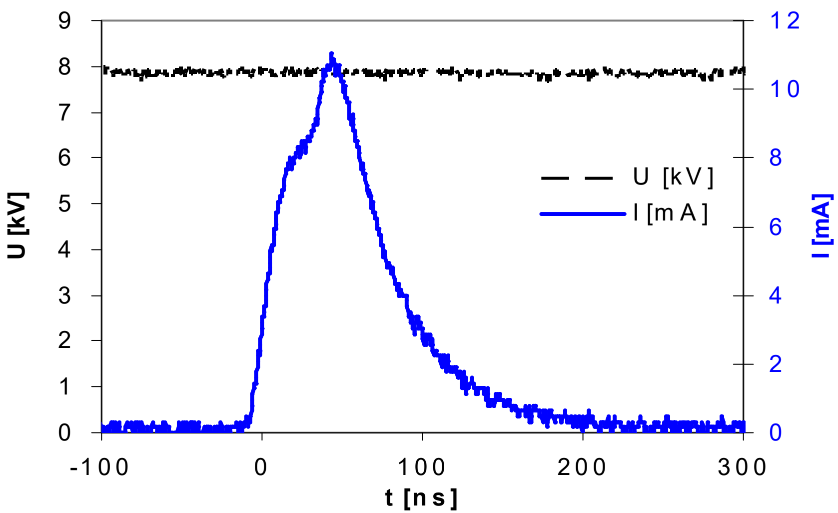
E. coli plate counting method

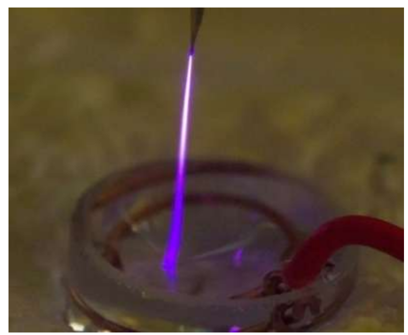
- Z. Machala et al., *J Phys. D* 2019

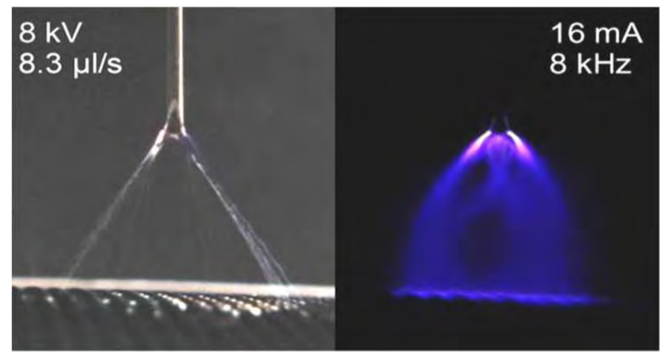
Streamer Corona Discharge (SC)

- Needle – plate, mesh, water electrodes
- Ambient air, p = 1 atm
- U = const ~ 5-10 kV,
- I_{mean} ~ 10-200 mA, I_{max} ~ 10-250 mA
- Pulses, f ~ 5-20 kHz, P ~ 0.1-1 W
- nonequilibrium cold plasma
- Easily combined with **water electrospray (ES)**





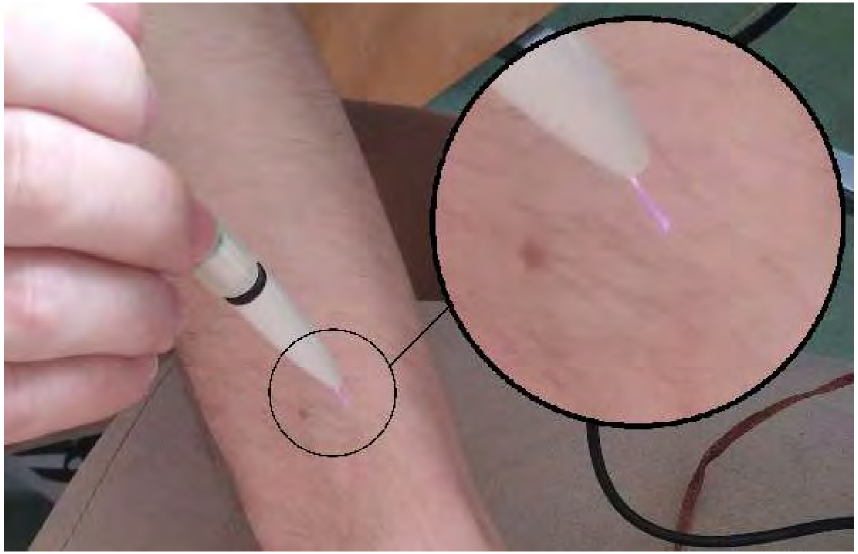




- B. Pongrac et al., *IEEE Trans. Plasma Sci*. 2011
- Z. Machala et al., *IEEE Trans. Plasma Sci.* 2008

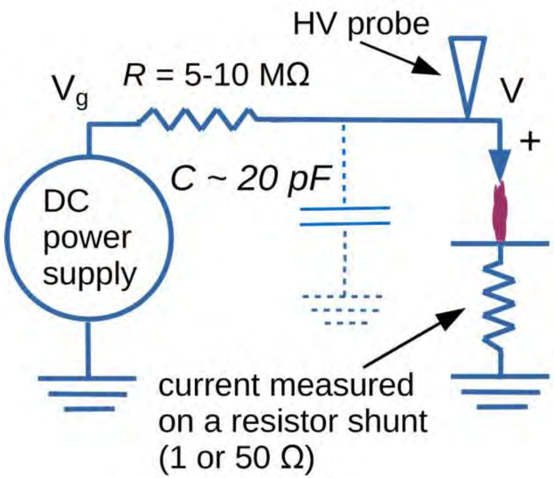
“Corona pen” portable plasma source

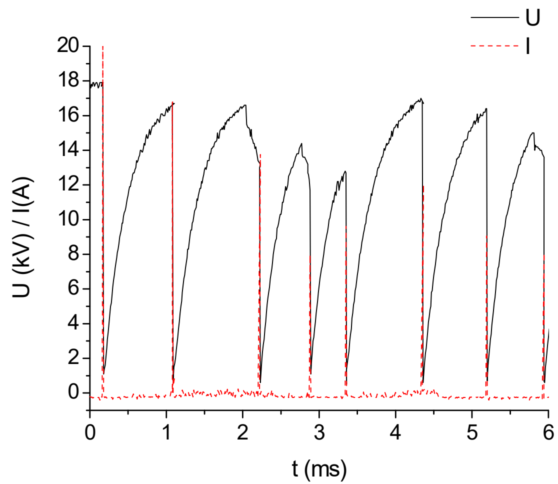
- Positive streamer corona – cold air plasma
- Average current ~ 100 mA, pulse frequency 5-30 kHz
- Safe, lightweight (<1 kg), portable, low-cost, optional on 12V battery power, low energy consumption (P < 1 W)
- **Antimicrobial effects** in ~1 min exposure
  - Tested on bacteria in water, biofilms, human skin wound healing,
- **Antitumor effects on cancer cells** (Direct and PAM, PAPBS)

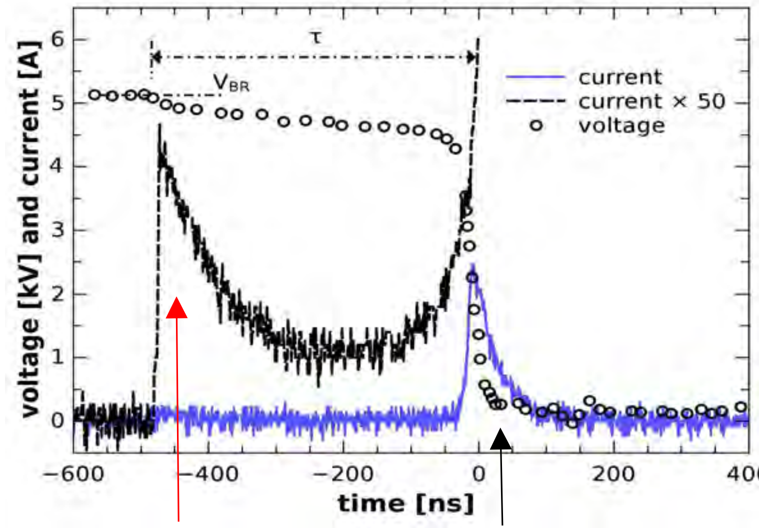


- Z. Machala and D.B. Graves: *Trends Biotechnol.* 2018
- K. Trebulova et al. *Plasma process. Polym.* 2023

DC Transient Spark Discharge (TS)





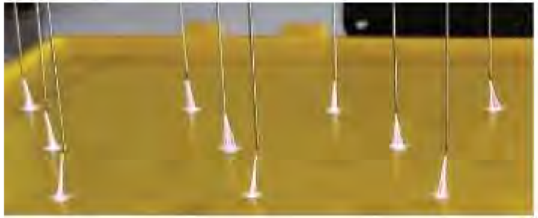


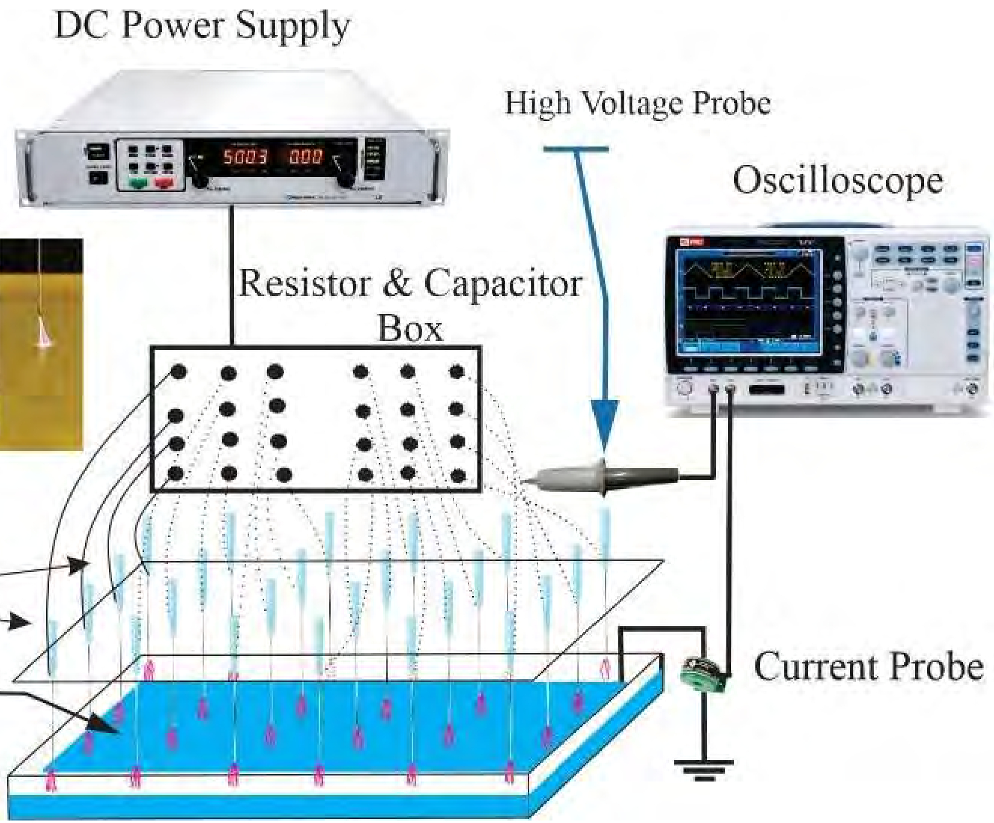
streamer and spark phases of TS

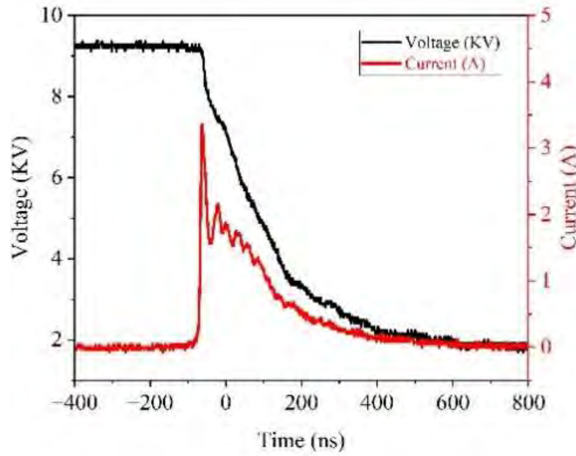
- **Periodic streamer-to-spark transition** – self-pulsing discharge
- Needle-to-plate, -mesh, water electrode
- Gas = air, 1 atm
- U_{max} ~ 12-18 kV, I_{mean} ~ 1-2 mA, I_{max} ~ 2-30 A, P ~ 1-2 W
- I-pulse duration **20-50 ns**, f ~1-10 kHz
- **nonequilibrium plasma**
- Can be combined with **water electrospray (ES)**

- Z. Machala et al,. *IEEE Trans. Plasma Sci.* 2008
- Z. Machala et al., *J Phys. D: Appl. Phys.* 2000
- M. Janda et al., *Plasma Sources Sci. Technol.* 2011, 2012

Multineedle Transient Spark – scaled-up PAW production







- 21 needles - each with its own R and C, common liquid electrode 210 mL
- Batch or liquid flow system
- Typical PAW preparation: 1 ml /1 min/ 1 needle/ 1 kHz/ 1 cm

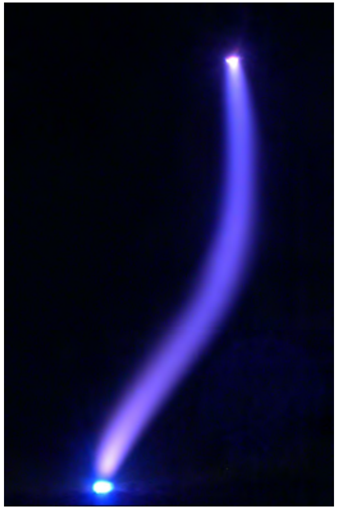
DC Glow Discharge

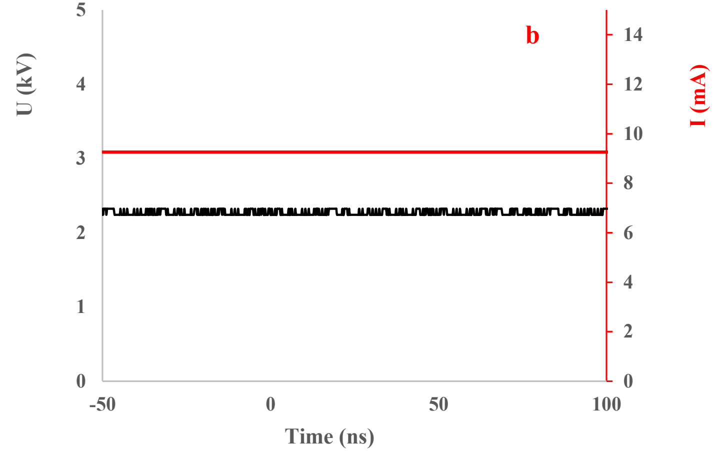
- Ambient air, p = 1 atm

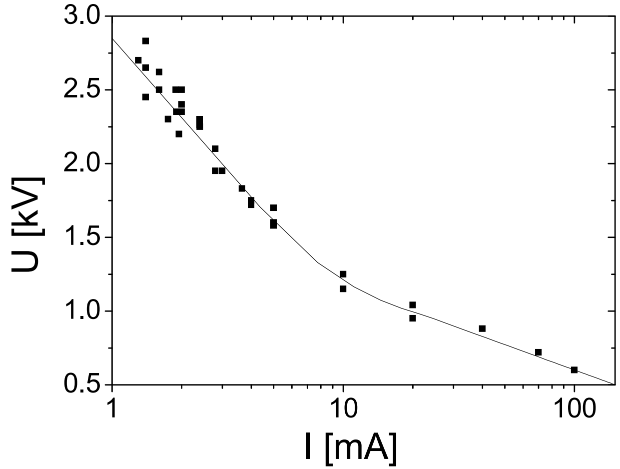
Glow Discharge (GD)

- Needle – plate, mesh, water electrodes
- **pulse-less**, U = 1.7-2 kV, I = 5-10 mA

  P ~ 9-20 W
- Cathode fall ~500 V (water cathode, air)
- Diffuse character
- $n_e \sim 2\times10^{12}$ cm^{-3}
- $T_g \cong 1950$ K, $T_e \sim 10{,}000$ K
- nonequilibrium, yet relatively hot plasma
- strong production of $^{\bullet}OH$ and H_2O_2







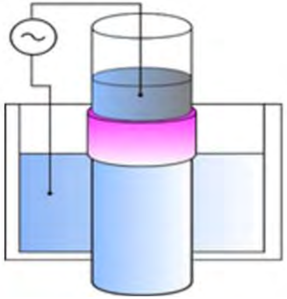
- Z. Machala et al., *J Phys. D: Appl. Phys.* 2000
- Z. Machala et al., *J. Advanced Oxid. Technol* 2004
- Z. Machala et al., *J. Molec. Spectrosc.* 2007

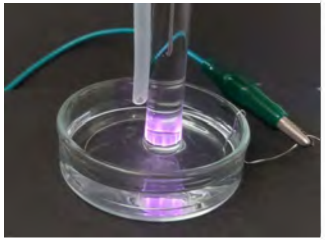
Surface DBD with liquid electrodes – catheter disinfection

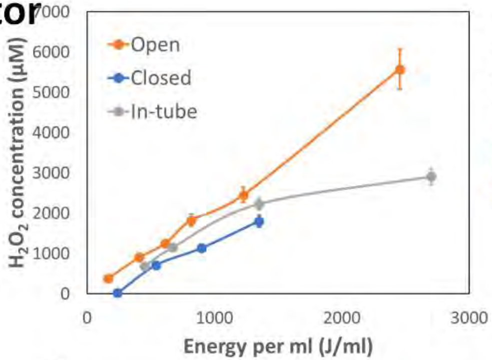
- Cold plasma at the circumference boundary of air-liquid-dielectric tube
- Disinfection of catheters
- Hydrophilization of tube materials

Tap water – weak buffer
Power **5 – 20 W**

Plasma outside tube / open reactor



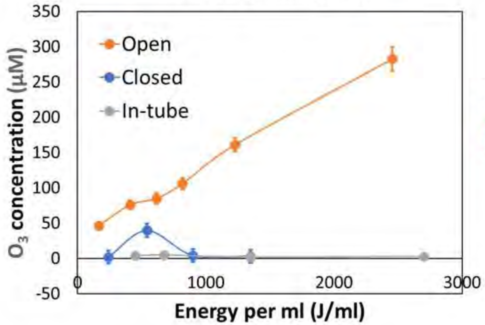




PAW: High H_2O_2, high O_3, high NO_2^-

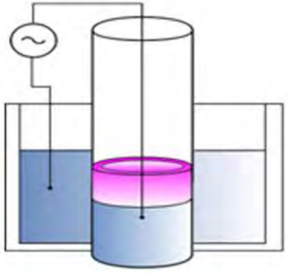
Peroxone process at pH > 5.5:
$H_2O_2 + 2\ O_3 \rightarrow 2\ OH + 3\ O_2$

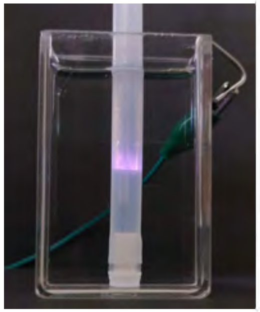
Plasma outside tube / closed reactor

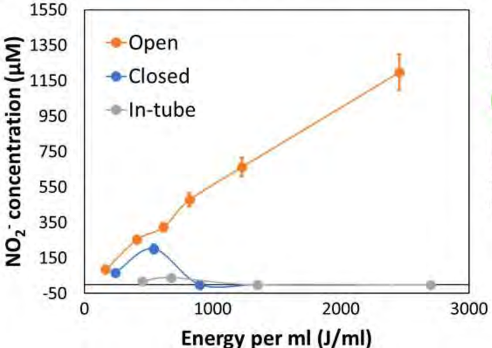


PAW: Low H_2O_2, low O_3, low NO_2^-

Plasma inside tube / closed reactor





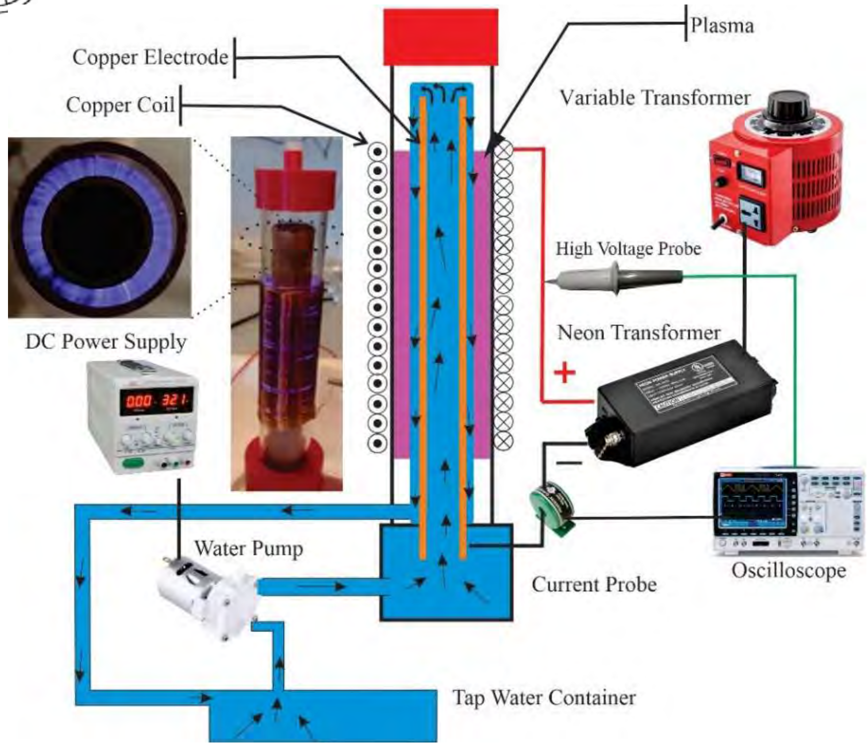


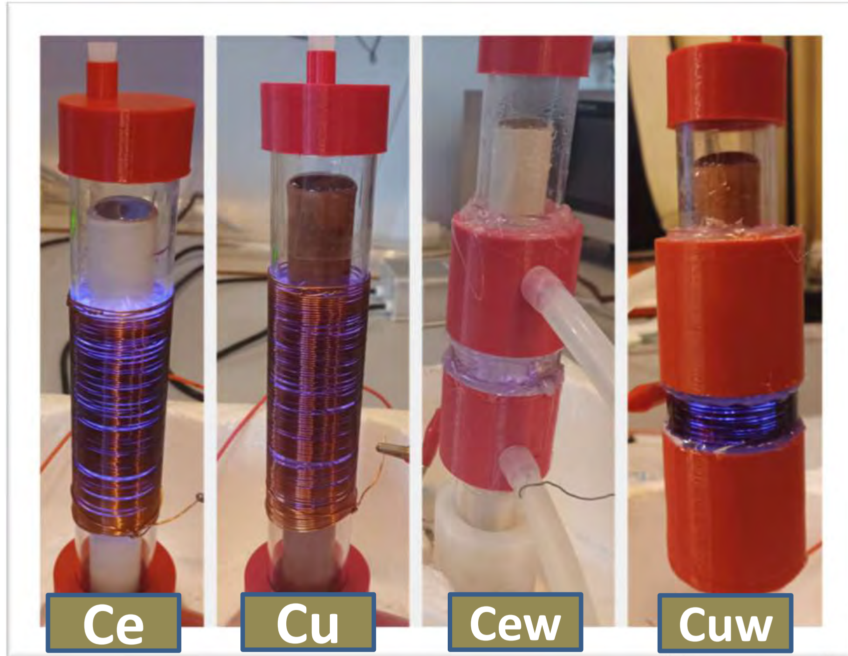
PAW: Medium H_2O_2, very low O_3 and NO_2^-

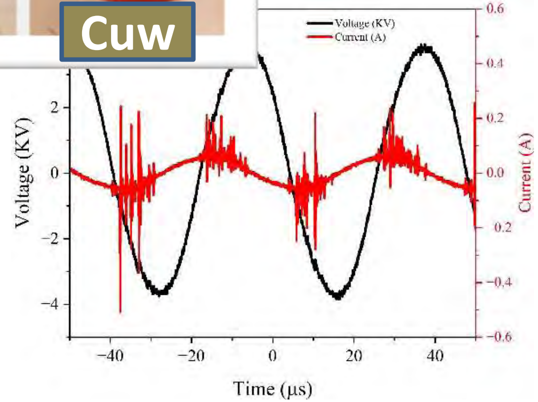
Increased evaporation to the limited volume ➔higher H_2O_2

- O. Galmiz et al. , *J Phys. D: Appl. Phys.* 2016
- O. Galmiz et al. , *Plasma Sources Sci. Technol.* 2025

Fountain DBD with liquid electrode



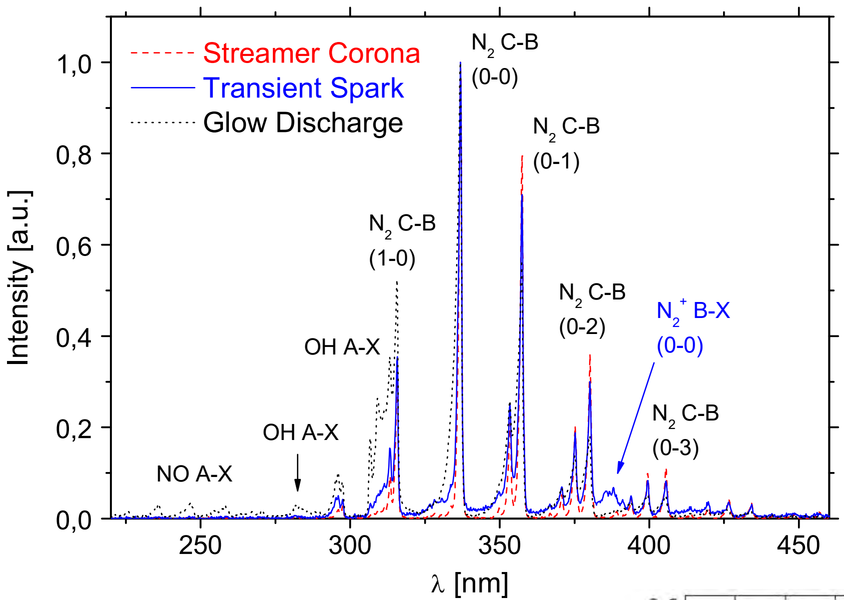


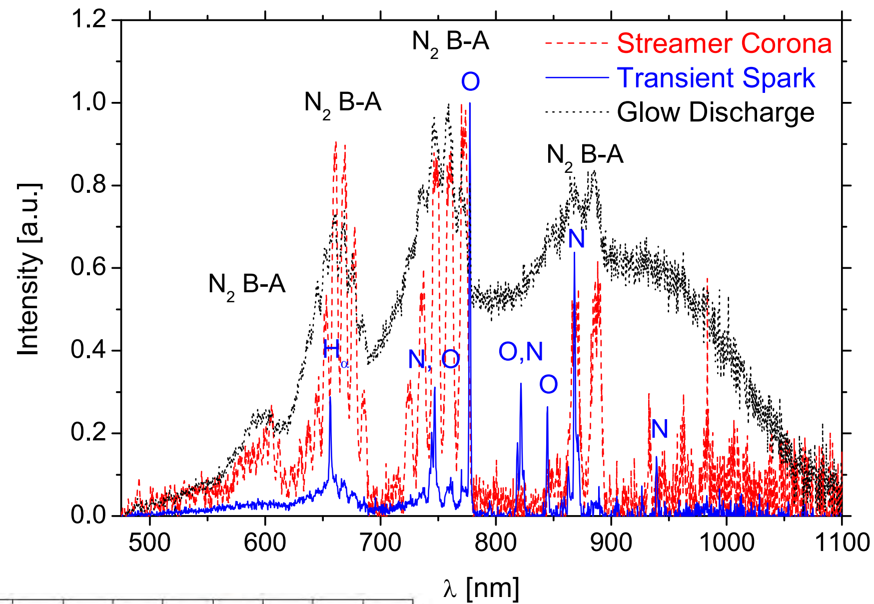


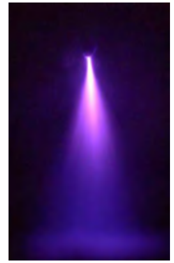
- Metal/ceramic inner tube with water film
- Glass/quartz outer tube
- Circulating water (large volume, typ. 1L)
- PAW production for bio-decontamination and seed germination
- RONS production depends on central electrode material (plasma power and number of microdischarges), and outside water cooling

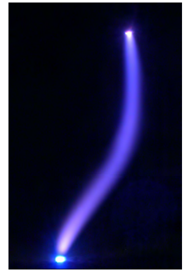
- S. Kooshki et al., *Env. Technol. Innov.* 2023
- S. Kooshki et al., *J. Water Proc. Eng.* 2024

Identification of RONS by Optical Emission Spectroscopy







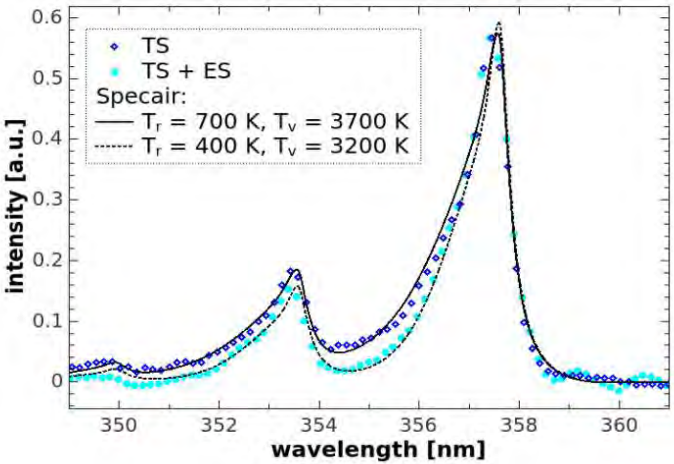


Molecular systems:

- N_2 ($C^3\Pi_u$ - $B^3\Pi_g$), N_2 ($B^3\Pi_g$ - $A^3\Sigma_u^+$); N_2^+ ($B^2\Sigma_u^+$ - $X^2\Sigma_g^+$)

Atomic lines:

- **H, O, N, OH** radicals – dissociations due to energetic electrons

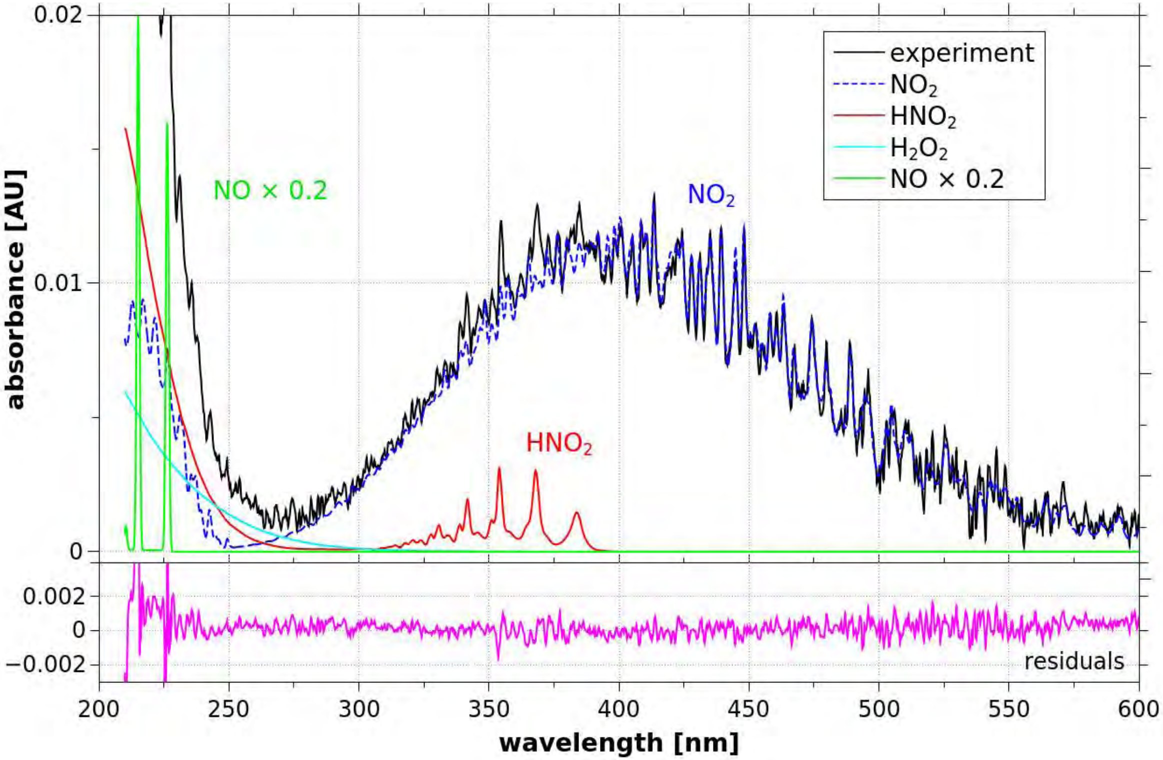


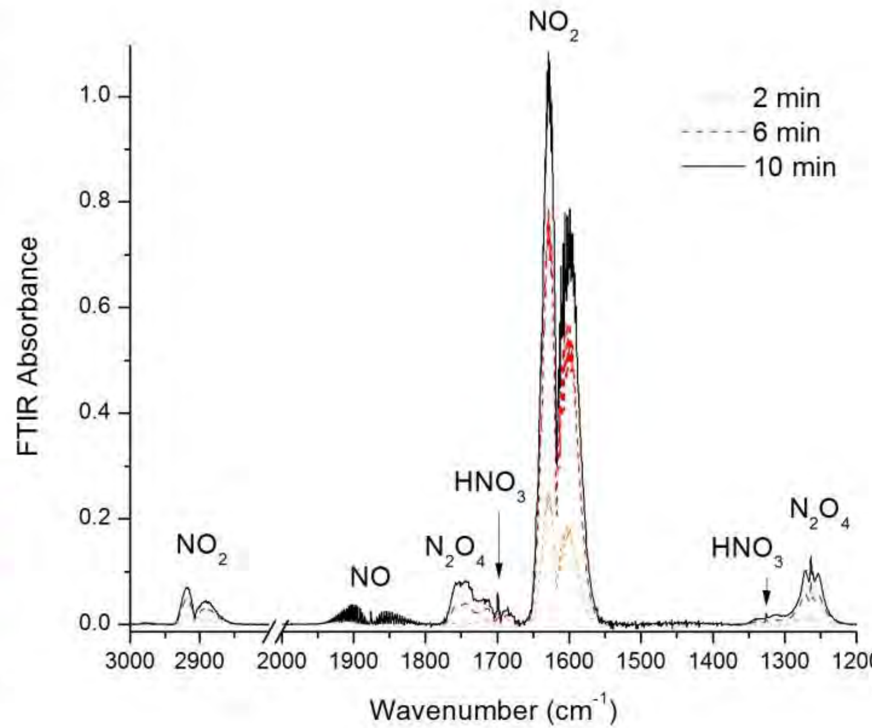
Emission spectra of TS, N_2 SPS bands and Specair fitting

Lower T_r with water ES

- Z. Machala et al., *J. Mol. Spectrosc.* 2007
- M. Janda et al., *Plasma Sources Sci. Technol.* 2014
- B. Tarabova et al., *Plasma Proces. Polym.* 2018

UV-vis/FTIR absorption of gaseous RONS

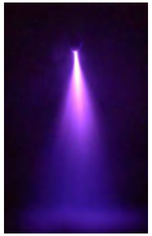


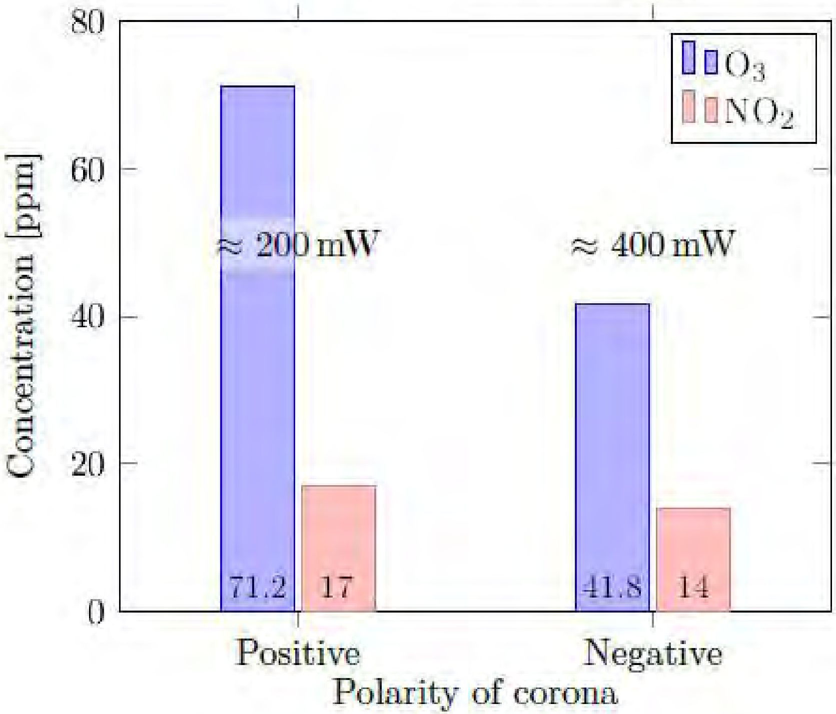


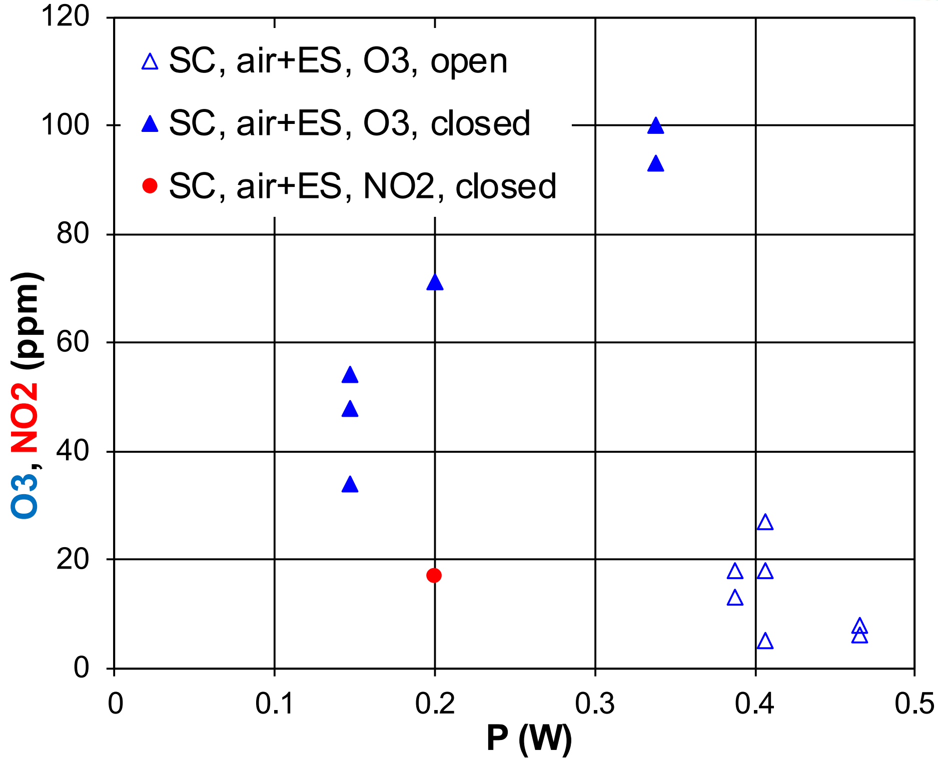
- UV-vis absorption – requires long-path cells (~0.75 m)
- FTIR – absorption depends on species concentration
- Ozone – good absorption in UV (256 nm) and IR (1060 cm^{-1})

- M. Janda et al., *Appl. Sci*. (2021)

Streamer corona generates O_3 and almost no NO





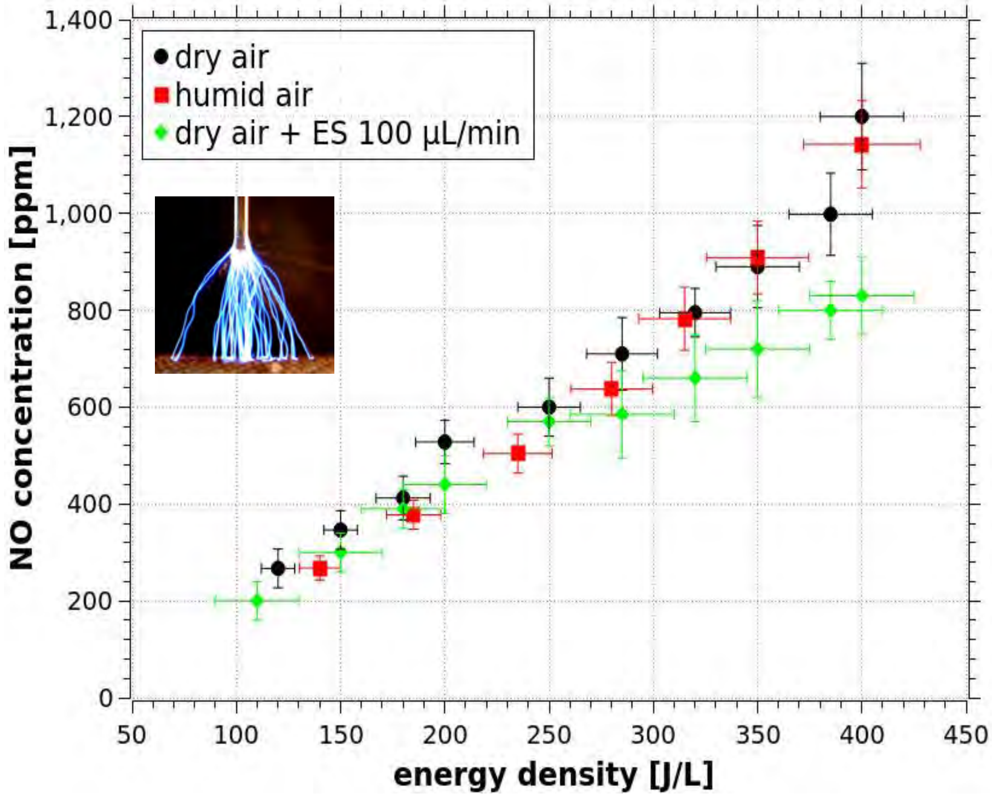


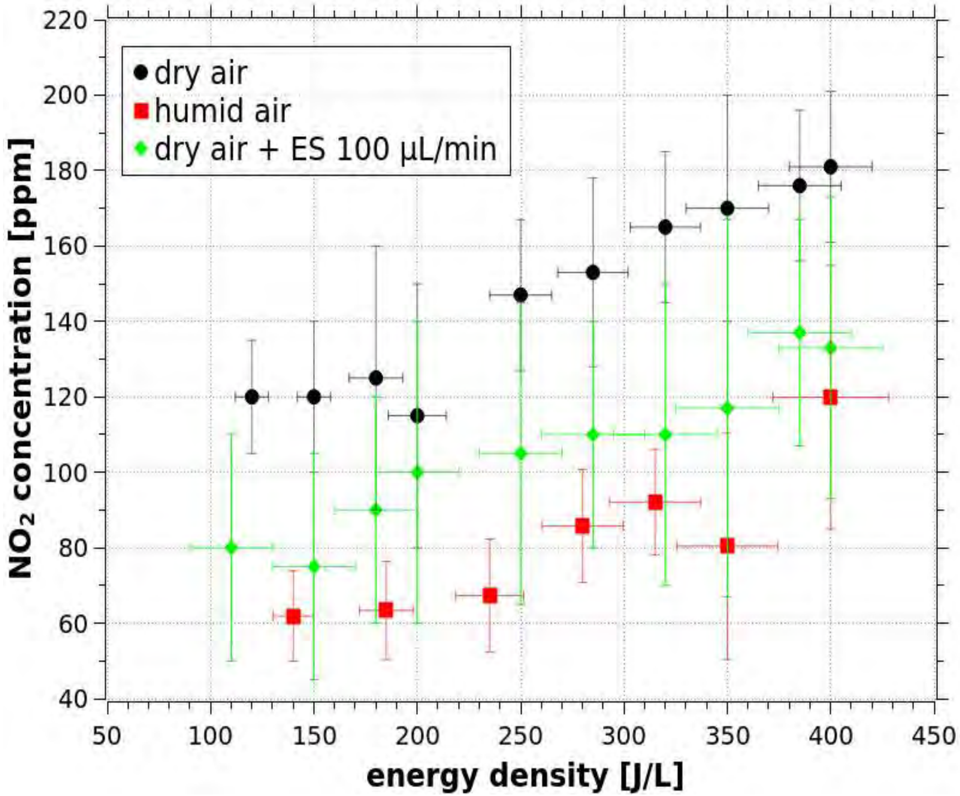
Gaseous O_3 and NOx formation in SC ambient air + water electrospray

- **O_3 and NO** formation **compete**: NO + O_3 → NO_2 + O_2
- Open air system generates less O_3 than closed chamber

- Z. Kovaľová et al., *Bioelectrochem.* 2016
- Z. Machala et al., *J. Phys. D: Appl. Phys.* 2019

TS generates NOx and no O_3

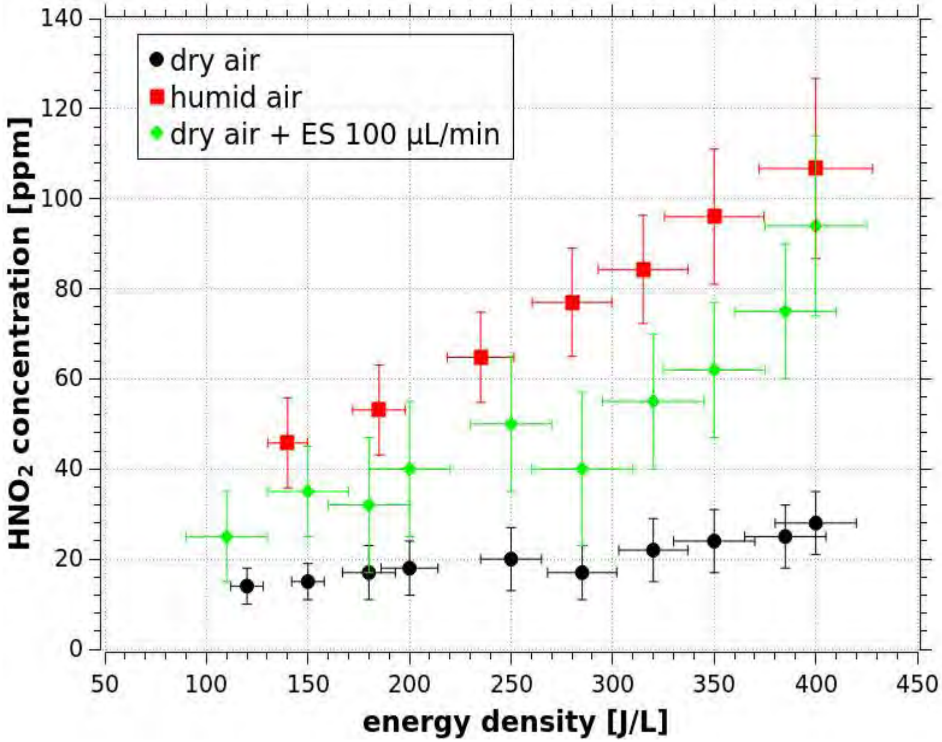


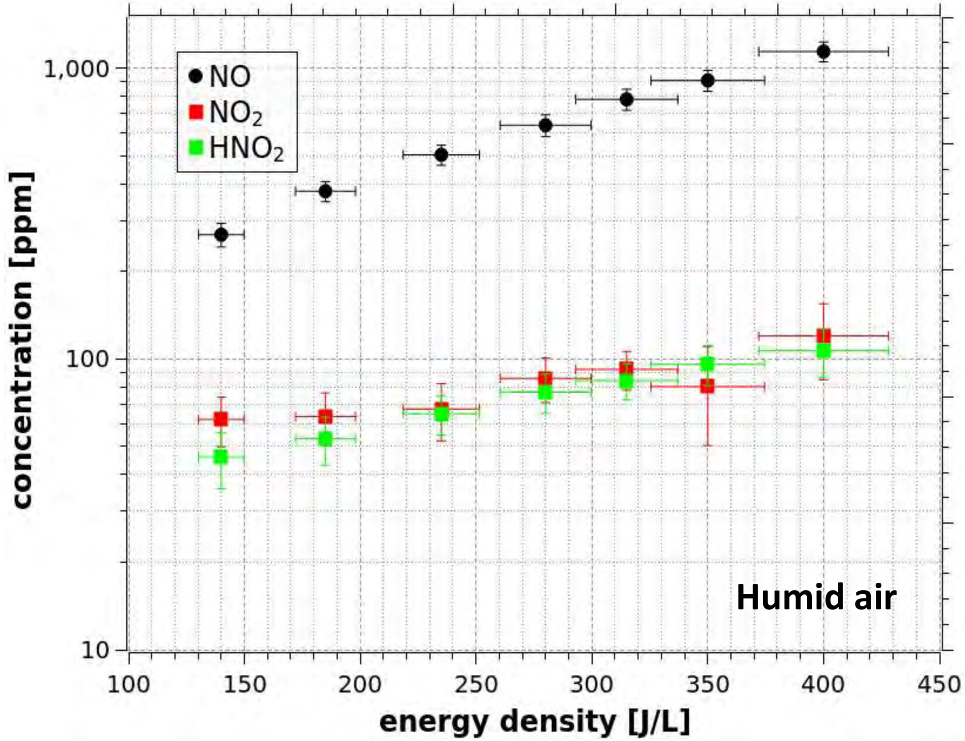


- NOx formation increases with energy density
- **NO** – almost no effect vs. **NO_2** – strong effect of humidity or water microdroplets

- M. Janda et al., *Plasma Chem. Plasma Process*. (2016)
- M. Janda et al., *Appl. Sci.* (2021)

Gaseous HNO_2 formation in TS

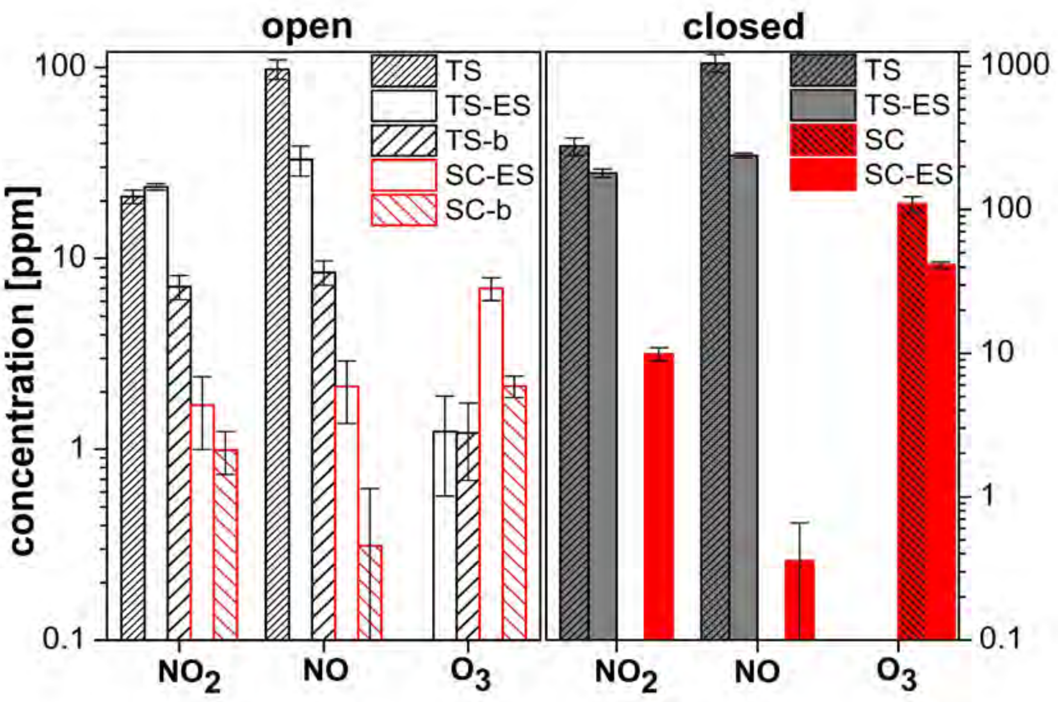




- Discharge in humid air and dry air with water ES – formation of **HNO_2**
- Gaseous NO / NO_2 - weak solvation in water – low NO_2^-
- HNO_2 – strong solvation in water – high NO_2^-
- **HNO_2 is the dominant source of NO_2^-** in PAW

- M. Janda et al., *Appl. Sci.* (2021)

TS vs. SC: open vs. closed gaseous RONS formation



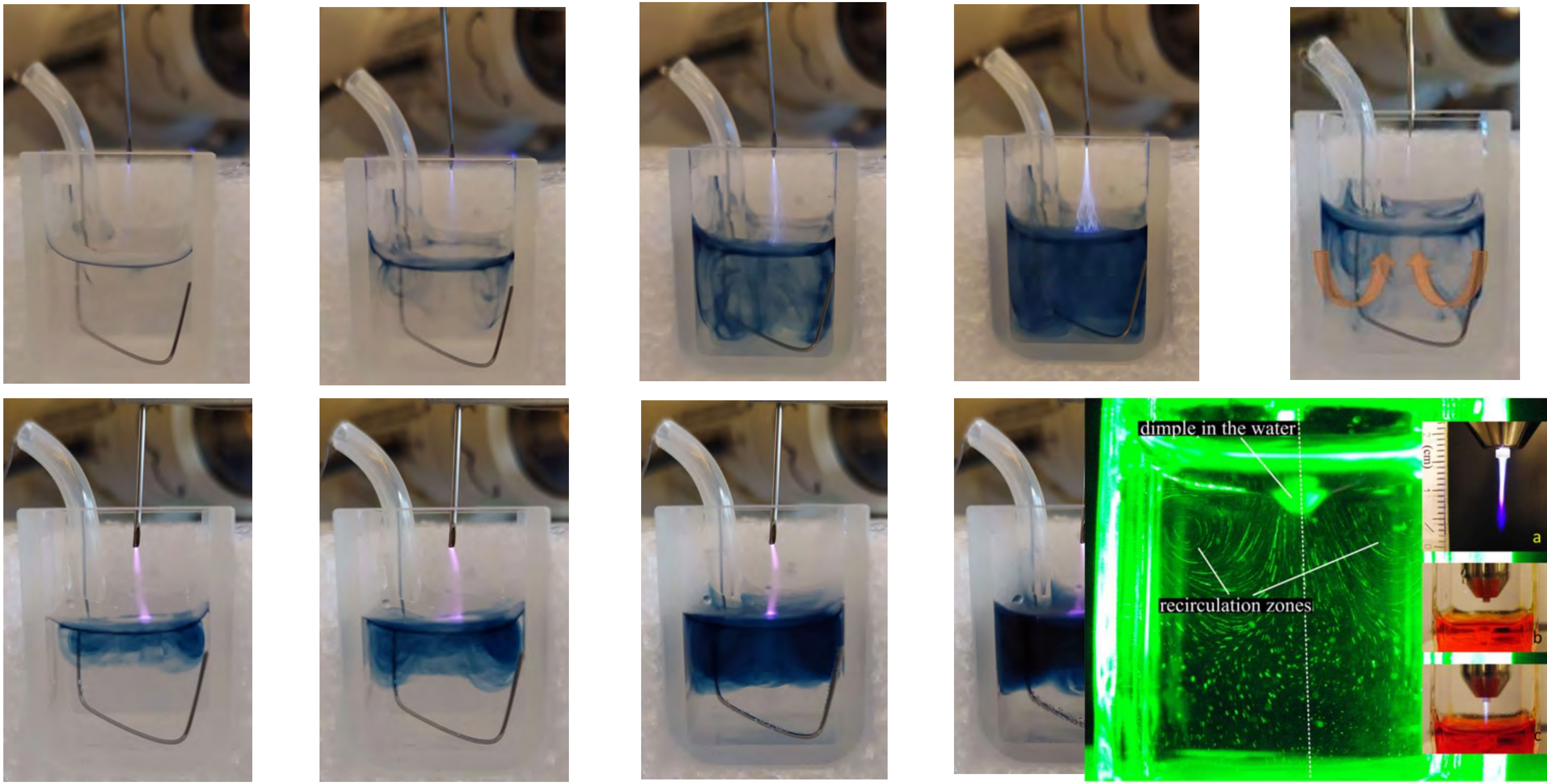
- **TS: NOx-dominated** chemistry,
  SC: O_3–dominated,
  O_3 and **NO** formation compete: NO + O_3 → **NO_2** + O_2
- Open air system generates about 10-100x less NO_x and O_3 than closed chamber

- Z. Machala et al., *J Phys. D* 2019
- M. Janda et al., *Appl. Sci.* (2021)

Visualization of ROS in PAW

TS
1 kHz, 2 W

GD
DC, 15 W



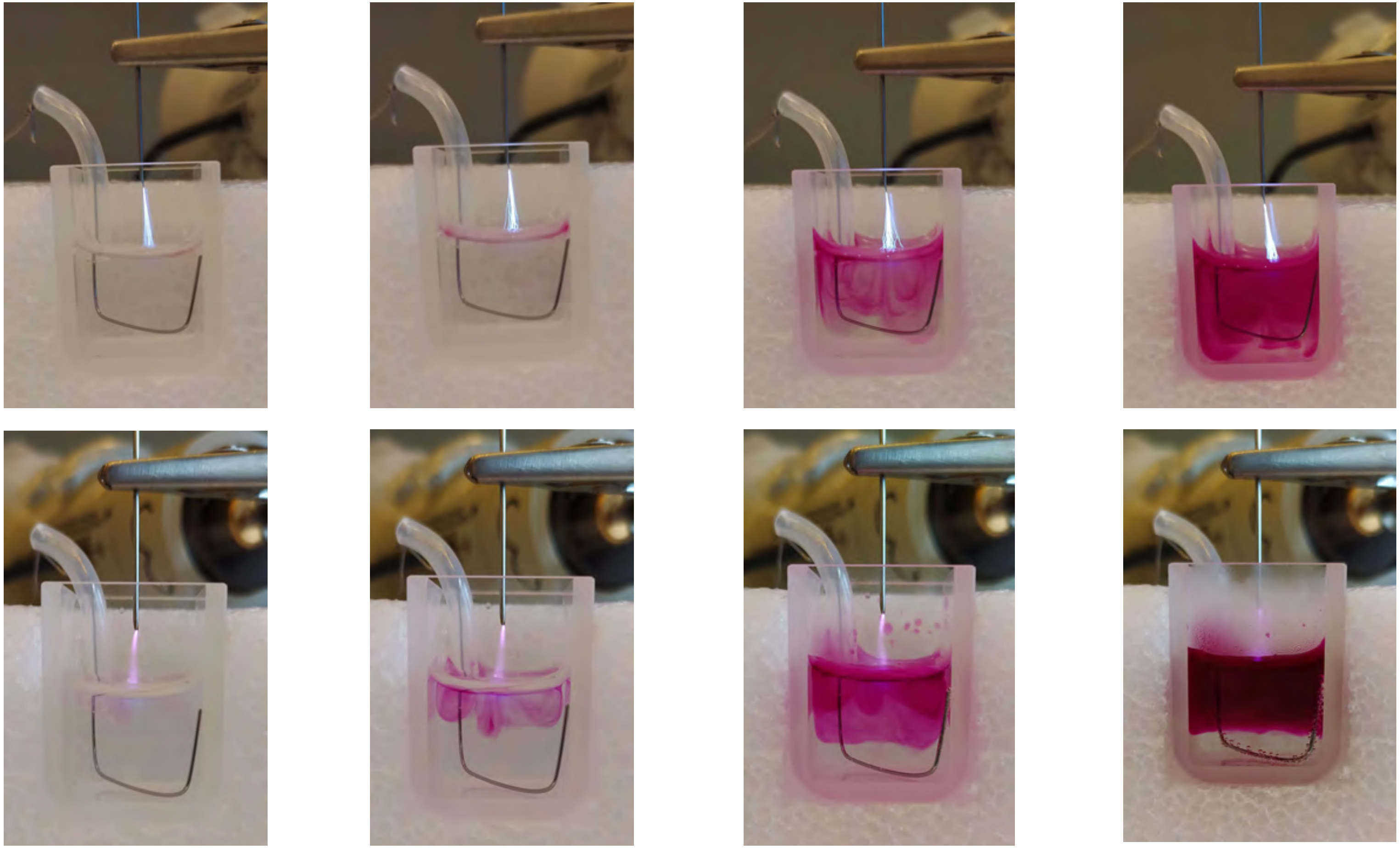
1s 5s 10s 30s

- H_2O_2 (and O_3) measured by KI Starch method
- Van Rens J F M et al., IEEE Trans. Plasma Sci. 2014

Visualization of RNS in PAW

TS
1 kHz. 2 W

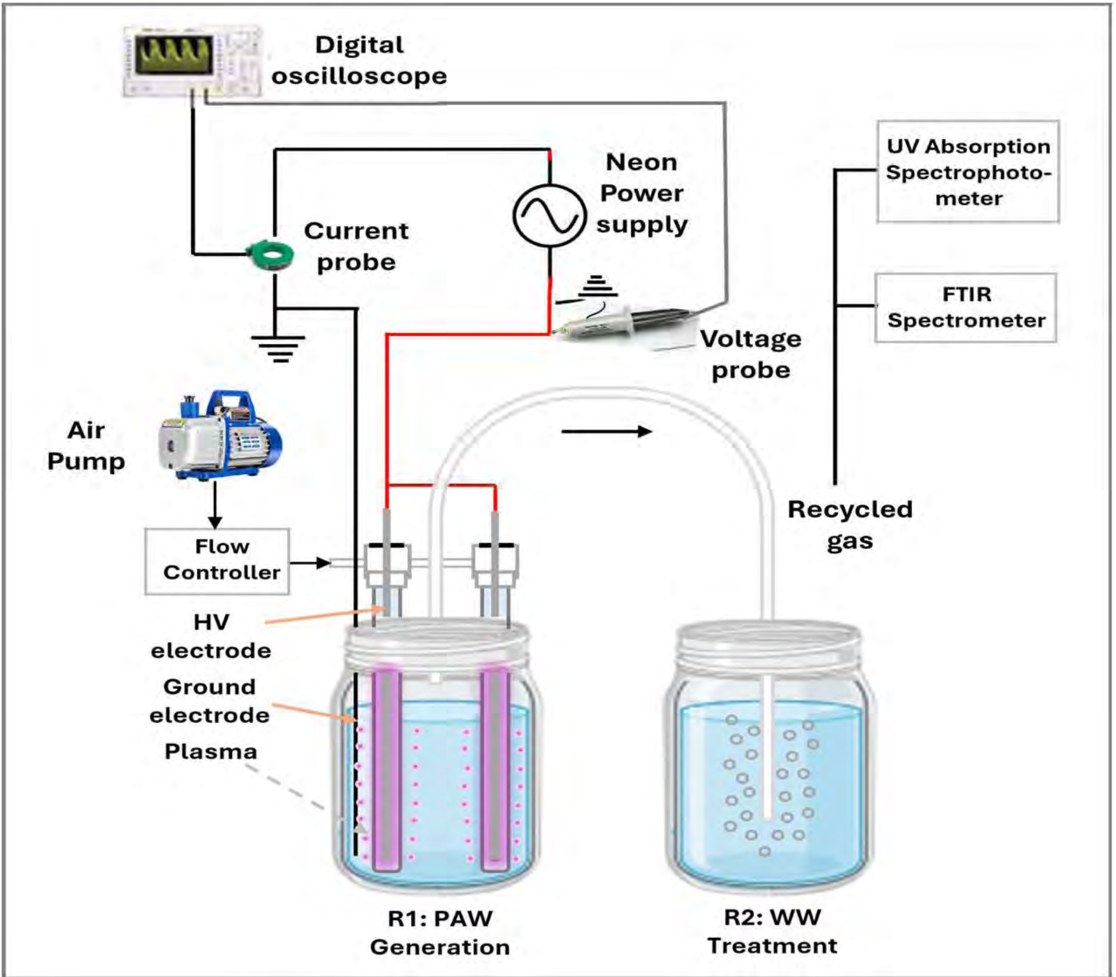
GD
DC. 15 W

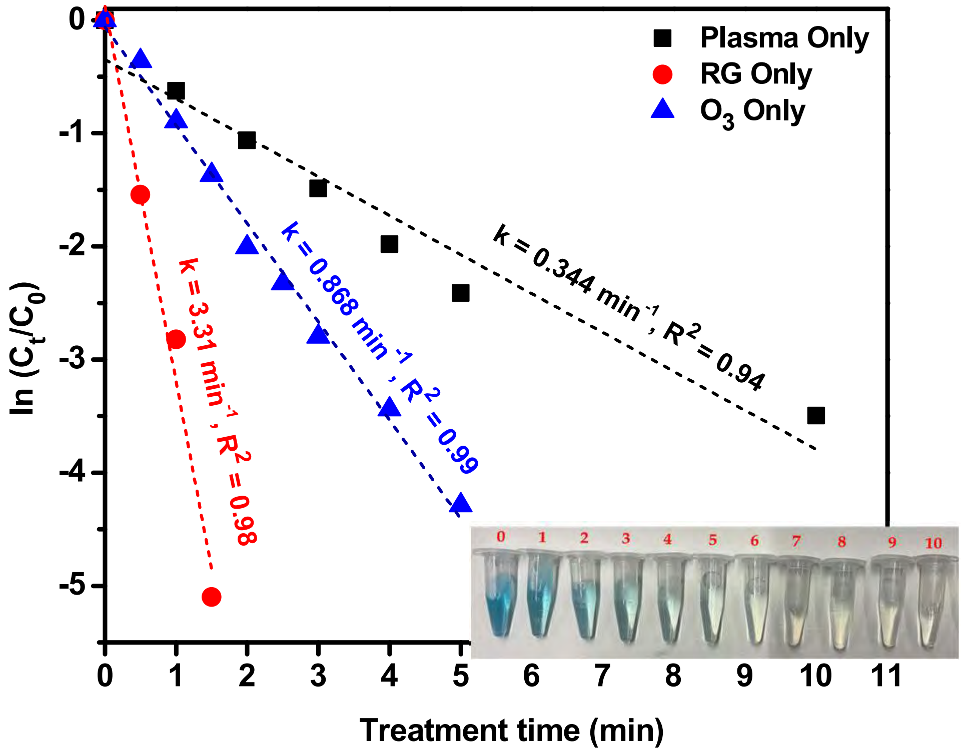


1s 3s 10s 30s

- **NO_2^-** measured by sulfanilamide and N-1-naphthylethylenediamine dihydrochloride (Griess reagent)

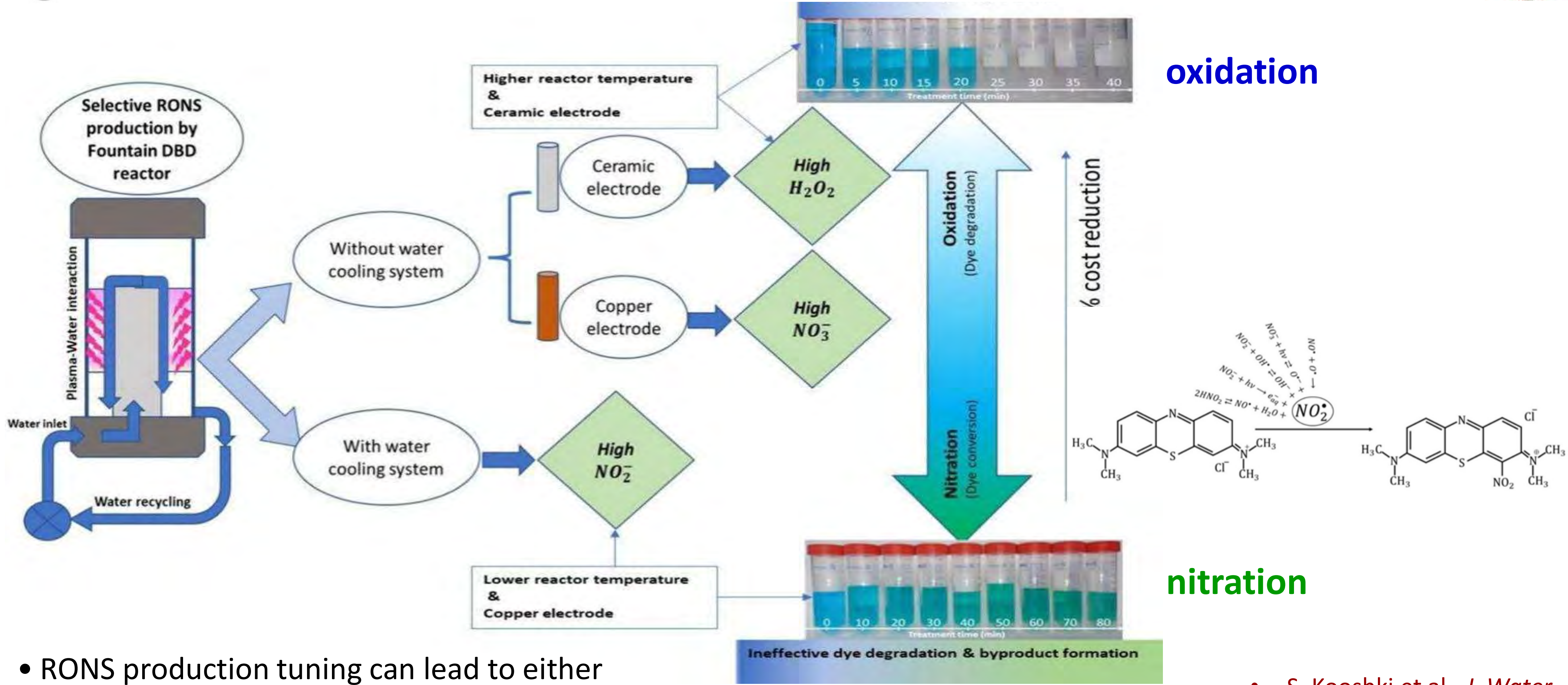
Plasma under Liquid via Microbubble Discharge: Enhanced Formation of RONS





- **Recycled Gas system**: rapid methylene blue degradation, driven by enhanced •OH formation at the microbubble interface
- Recycled Gas > ozonation > plasma-bubbled treatment

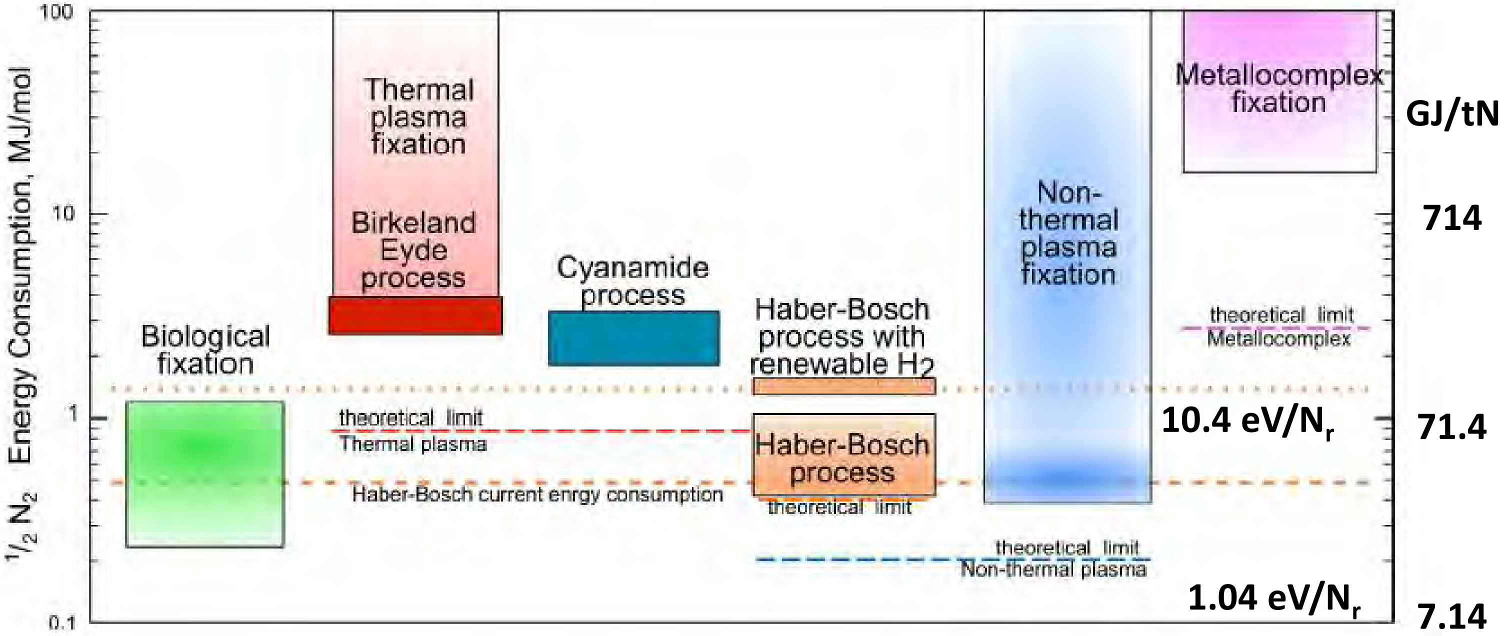
Fountain DBD with liquid electrode: RONS tuning in PAW



- RONS production tuning can lead to either dominant **oxidation** or **nitration** (shown on methylene blue discoloration)

- S. Kooshki et al., *J. Water Proc. Eng.* 2024

Existing and alternative methods for greener N-fixation



NH_3 currently manufactured via Haber-Bosch high pressure, high temperature catalytic process reacting H_2 and N_2:

- ***1% world energy use***
- ***3-5% world CH_4 use***

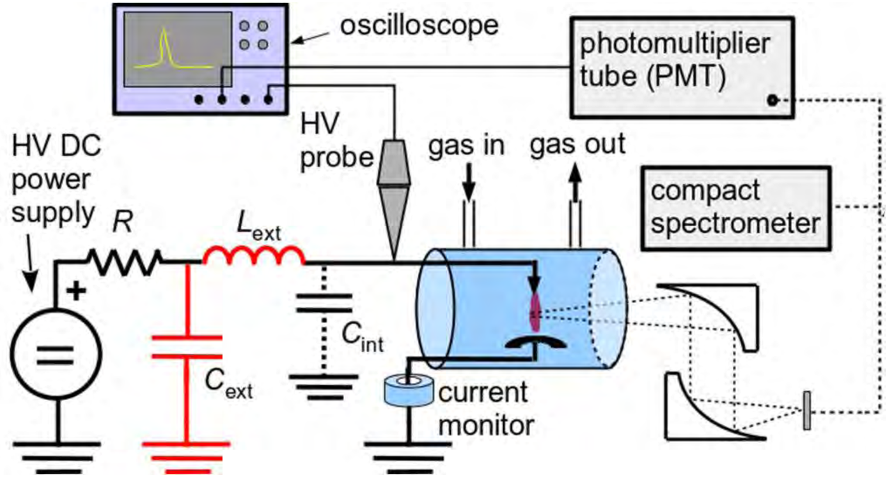
1 MJ/mol N_r = 71.4 GJ/tN_r = 10.4 eV/N_r

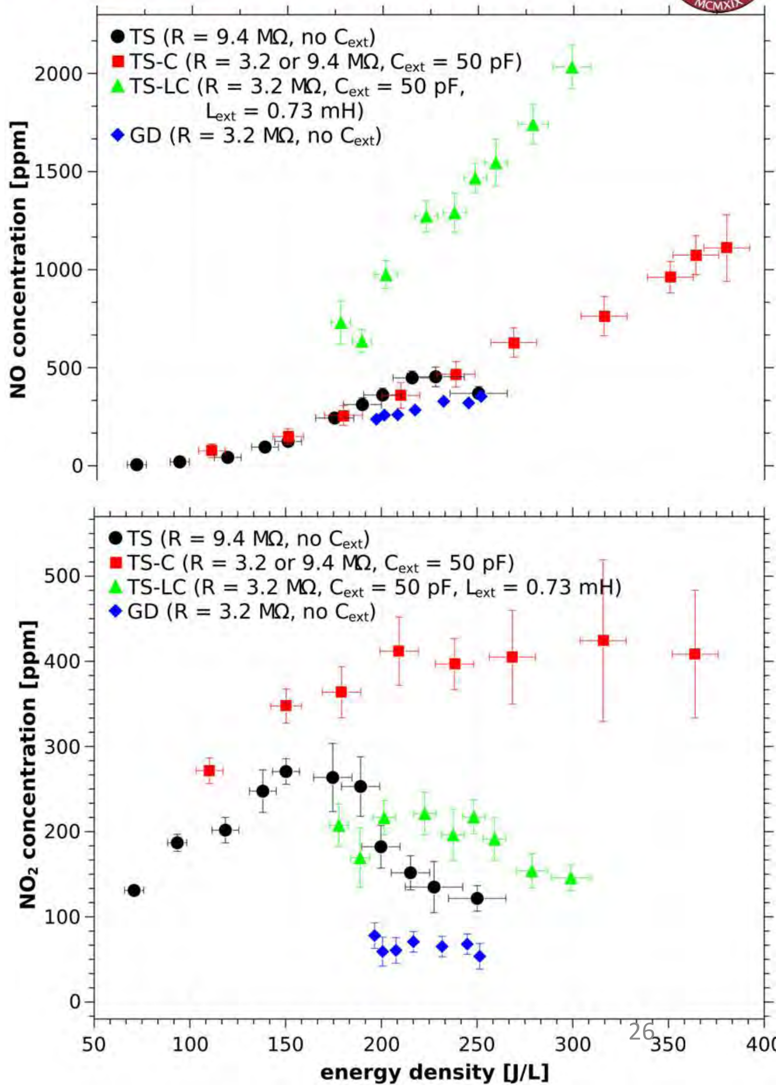
1 MJ/mol N_r = 6 x 10^{17} N_r/J

Non-thermal plasma - a promising route!

- N. Cherkasov et al. *Chemical Engineering and Processing* 90 (2015) 24–33

TS with additional C and L: stronger NO formation

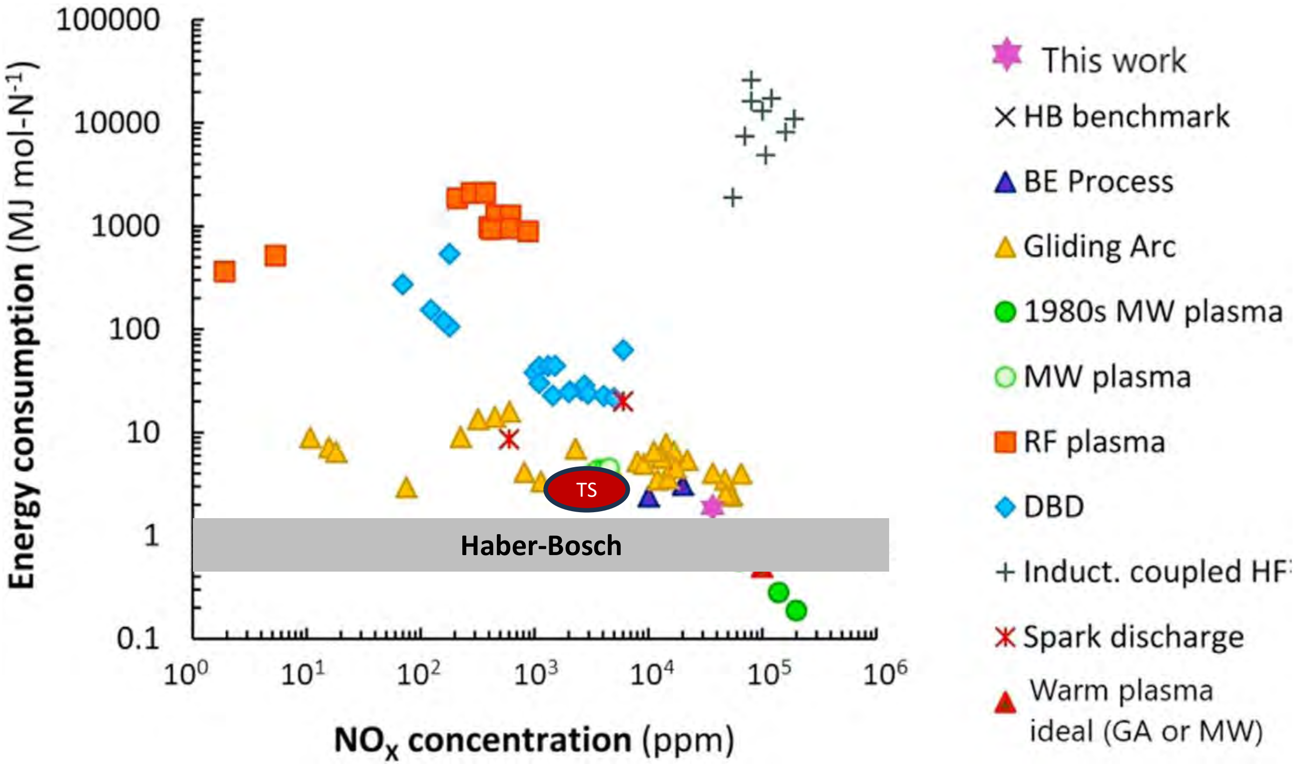




- **NO production is boosted** by the **addition of a capacitor and an inductor** to the TS electrical circuit.
- NO produced per joule per volume is doubled
- The yield of NO increased - the modified circuit enables higher discharge currents.
- This simple modification of the driving circuit may have potential for optimizing the plasma chemistry and for scaling up N-fixation from air.

- M. Janda et al., J. Phys D. *Appl. Phys*. (2023)

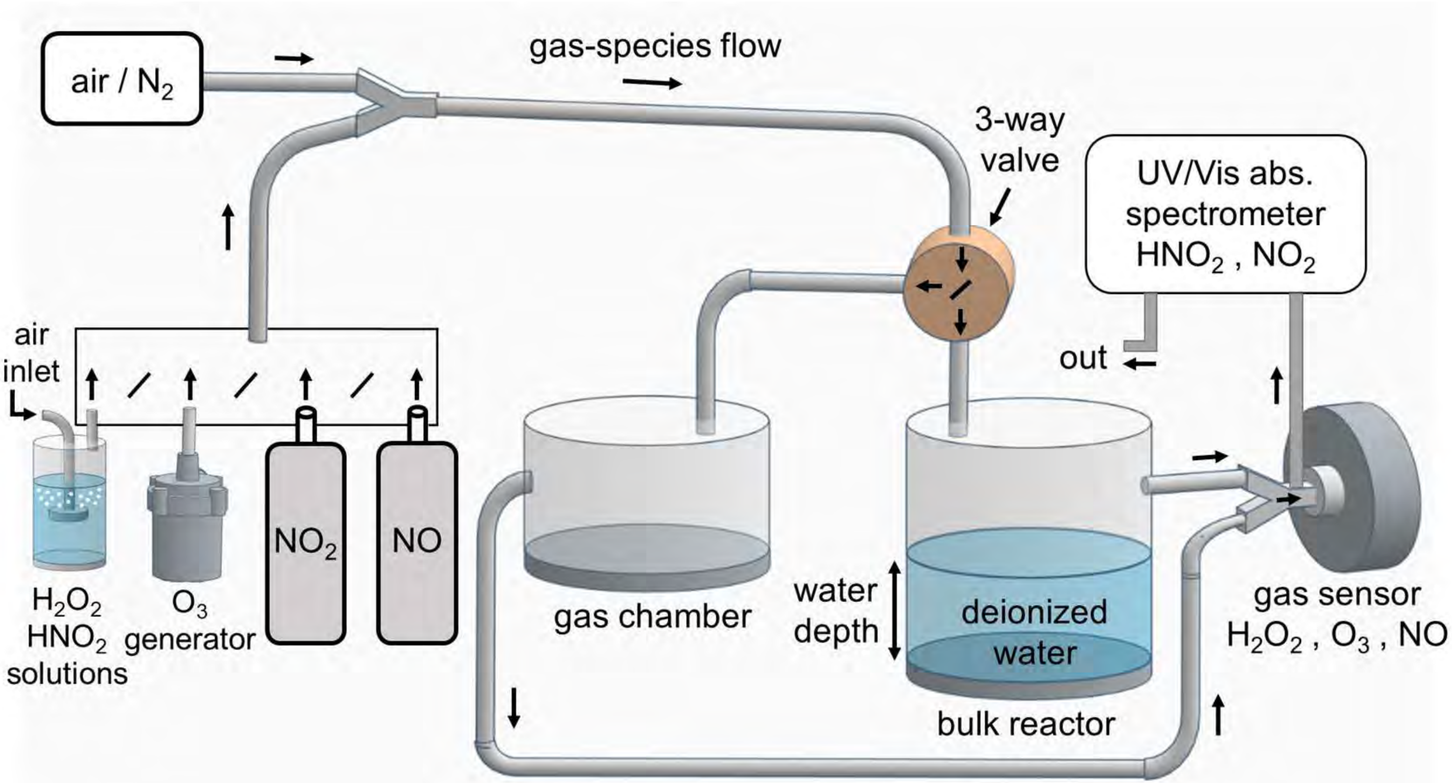
Energy costs of N-fixation by TS-LC discharge



NOx production in different types of discharges
+ added value of TS-LC

- S. Kelly & A. Bogaerts, *Joule* 2021
- M. Janda et al., J. Phys D. *Appl. Phys*. (2023)

RONS transport into bulk water



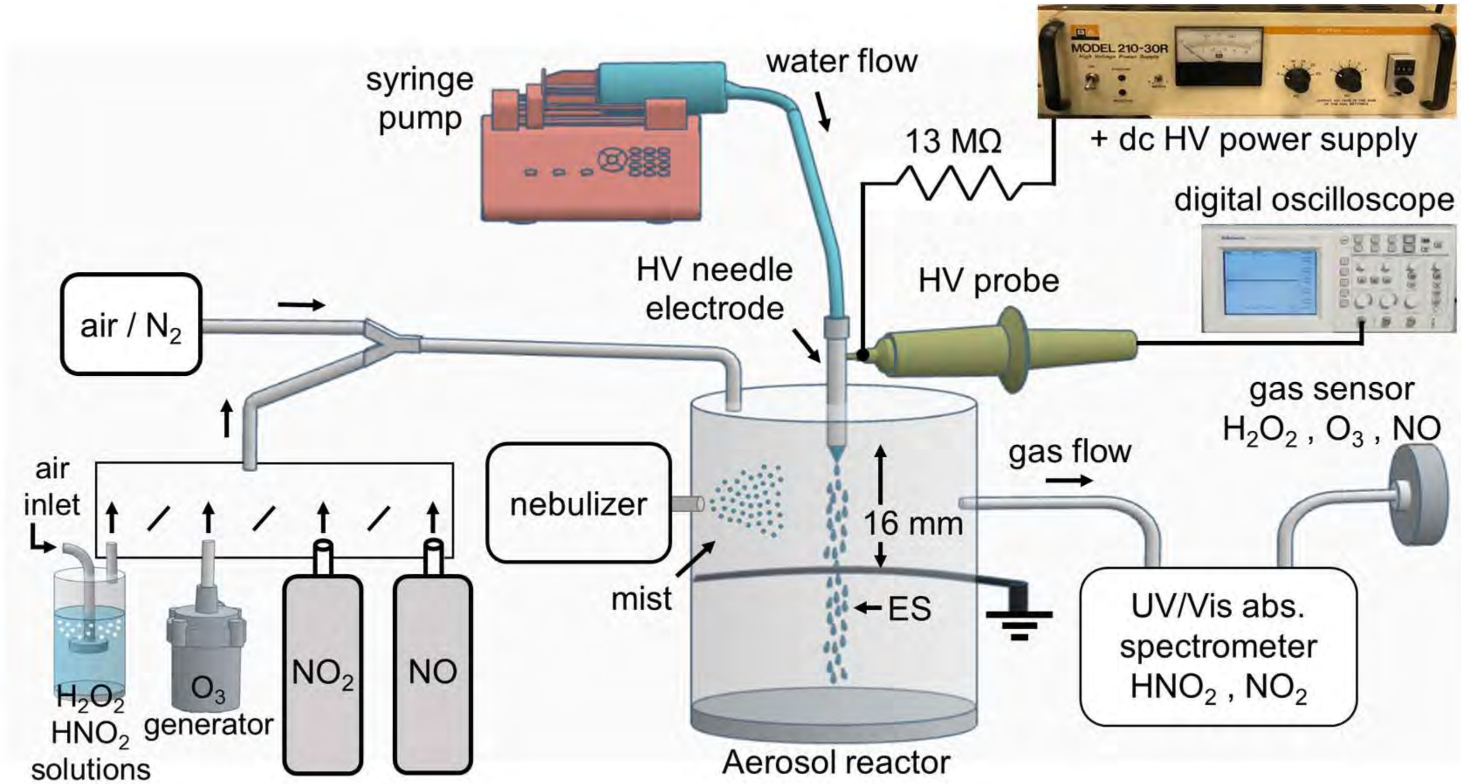
H_2O_2 : 9.8 M
HNO_2 : 20 mM

External sources of
ozone (450 ppm)
H_2O_2 (100 ppm)
HNO_2 (100 ppm)
NO_2 (250 ppm)
NO (600 ppm)

- **Bulk** water
- Detection of gaseous **O_3, H_2O_2, HNO_2, NO, NO_2**: electrochemical gas sensors, UV-vis absorption, FTIR
- Analysis of aqueous RONS
  O_3: indigo blue reagent (λ_{abs} = 600 nm)
  H_2O_2: $TiOSO_4$ (λ = 407 nm)
  NO_2^- : Griess reagent λ = 540 nm

- M.E. Hassan et al., *Water* 2021

RONS transport into microdroplets



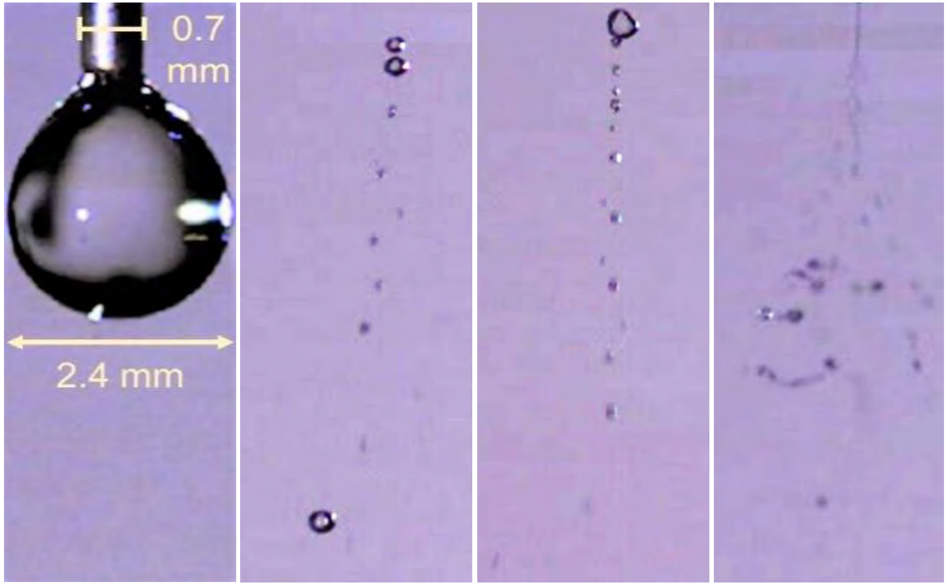
H_2O_2 : 9.8 M
HNO_2 : 20 mM

External sources of
ozone (450 ppm)
H_2O_2 (100 ppm)
HNO_2 (100 ppm)
NO_2 (250 ppm)
NO (600 ppm)

- Water **microdroplets: electrosprayed/nebulized**
- Detection of gaseous **O_3, H_2O_2, HNO_2, NO, NO_2**: electrochemical gas sensors, UV-vis absorption, FTIR
- Analysis of aqueous RONS
  O_3: indigo blue reagent (λ_{abs} = 600 nm)
  H_2O_2: $TiOSO_4$ (λ = 407 nm)
  NO_2^- : Griess reagent λ = 540 nm

- M.E. Hassan et al., *Water* 2021

Electrospray



0 kV 9 kV 11 kV 13 kV

High speed camera imaging, 300 µL/min

$E = 0$

- Constant droplet shape and volume (given by surface tension)

$0 < E < E_{onset}$

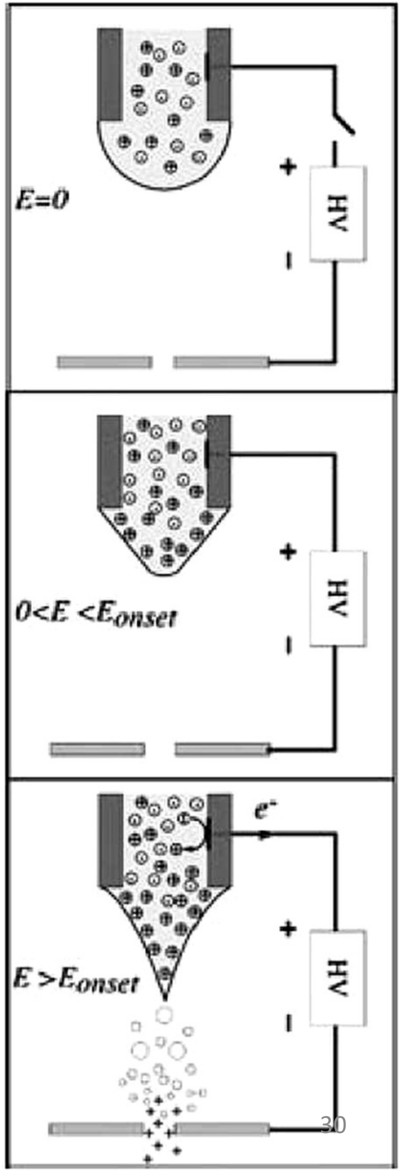
- Volume of droplet decreases (electrostatic pressure against capillary pressure)
- Dripping rate increases

$E \geq E_{onset}$

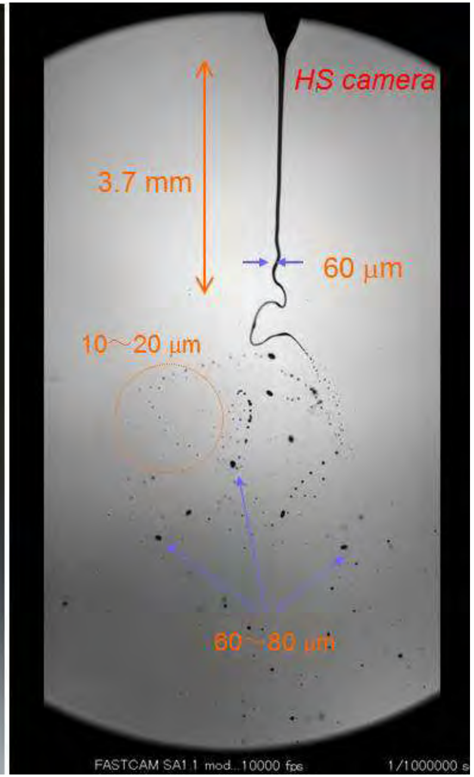
- Taylor cone formation (force balance)

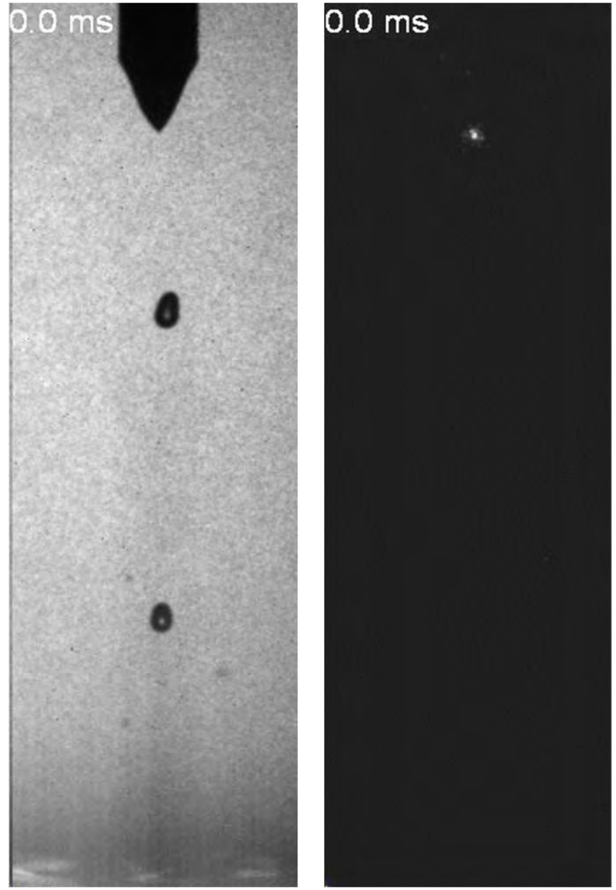
Static Taylor cone criterion

$$E_{onset} = \sqrt{\left(\frac{2\gamma \cos\alpha}{\varepsilon_0 \, r}\right)}$$



Electrospray



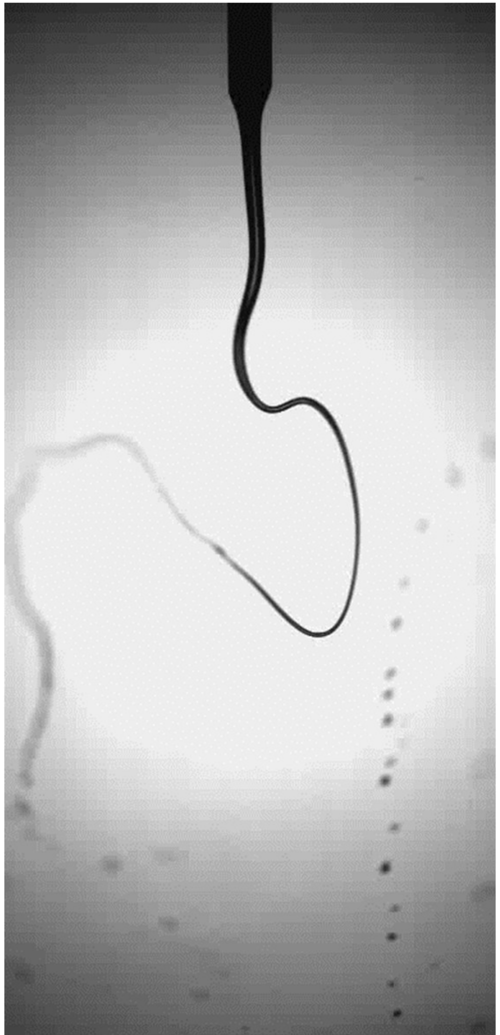


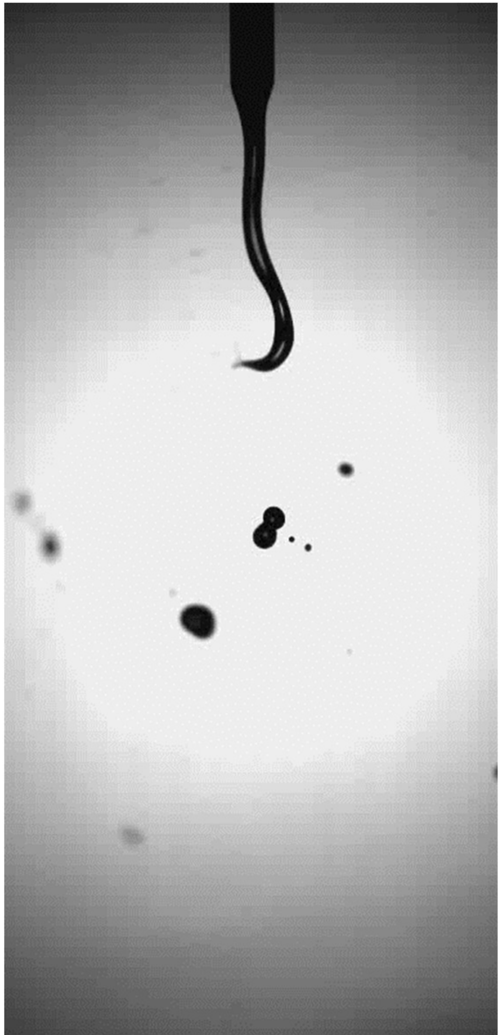
ICCD imaging

- B. Pongrac et al., *IEEE Trans. Plasma Sci*. 2011
- B. Pongrac et al., *J. Phys. D Appl. Phys.* 2014
- B. Pongrac et al., *J. Aerosol. Sci.* 2016
- A. Jaworek et al., *J. Phys. D Appl. Phys.* 2019

Electrospray : Influence of water conductivity

2 µS/cm,
4 ml/min,
14 kV





400 µS/cm,
4 ml/min,
14 kV

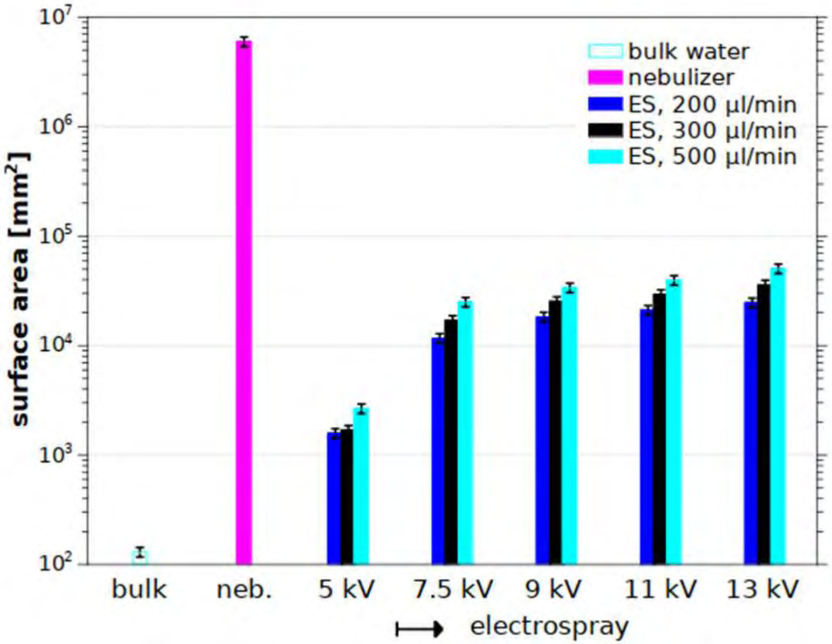
t_{exp} 1 µs

10 000 fps

1 s = 0.5 ms

- B. Pongrác et al., Eur. Phys. J. D 2014

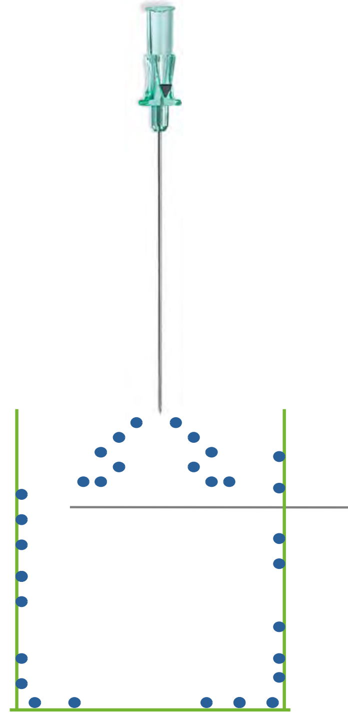
Surface area of ES/nebulized microdroplets vs. bulk



Total surface area of water microdroplets formed by ES, nebulizer and bulk water, 1 min, different *water flow rates* and *applied voltage*

- Nebulizer 1-5 µm microdroplets << ES

- M.E. Hassan et al., *Water* 2021
- M.E. Hassan et al., *Plasma Chem. Plasma Proc.* 2024

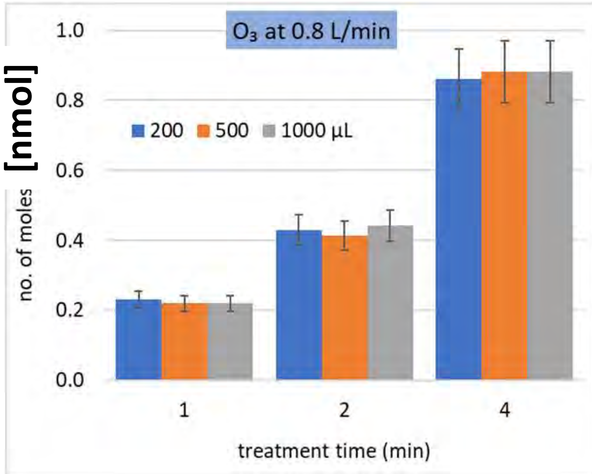


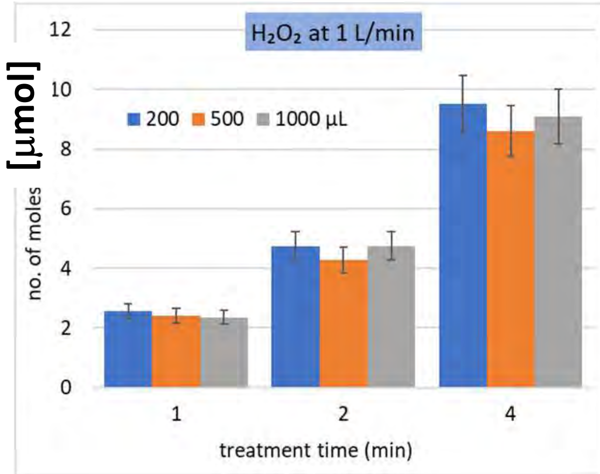
- Solvation (transport) of RONS is determined by the **surface area x treatment time**
- Total microdroplet treatment time: both **flying (ES) time << sitting on the bottom/walls time** contribute to the solvation

Solvation of O_3 / H_2O_2 into water bulk vs. microdroplets

O_3 H_2O_2

bulk



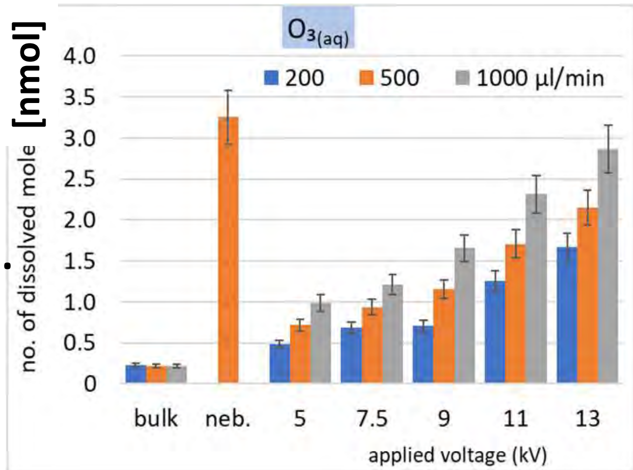


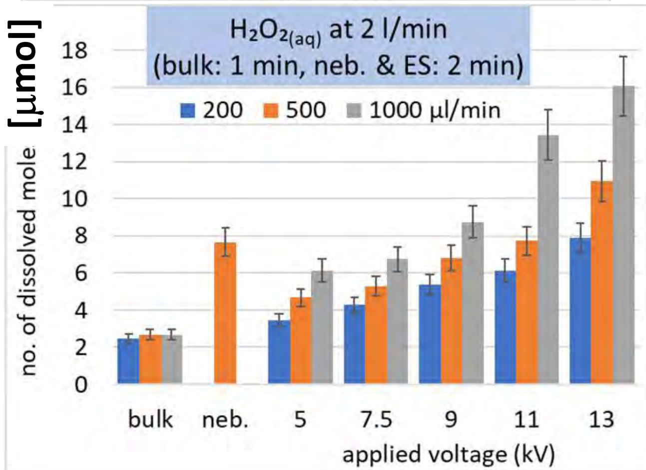
H_2O_2 : $k_H \approx 9 \times 10^2$ mol/m^{3}Pa

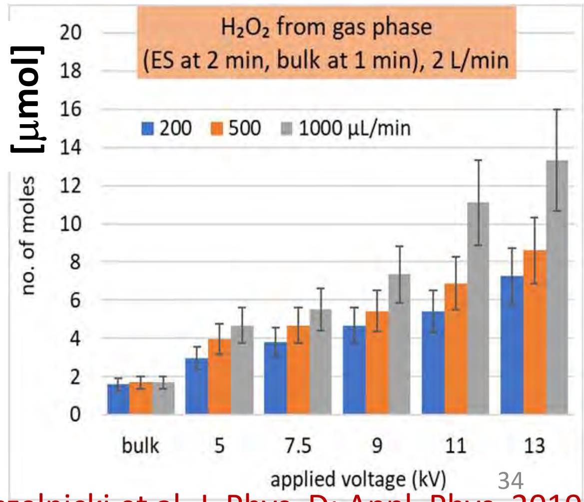
O_3 : $k_H \approx 10^{-4}$ mol/m^{3}Pa

- O_3 is gas–water interface area-dependent – low k_H and slow diffusion
- H_2O_2 is very soluble - **depletion from the gas** and slow diffusion into water

ES / nebul.



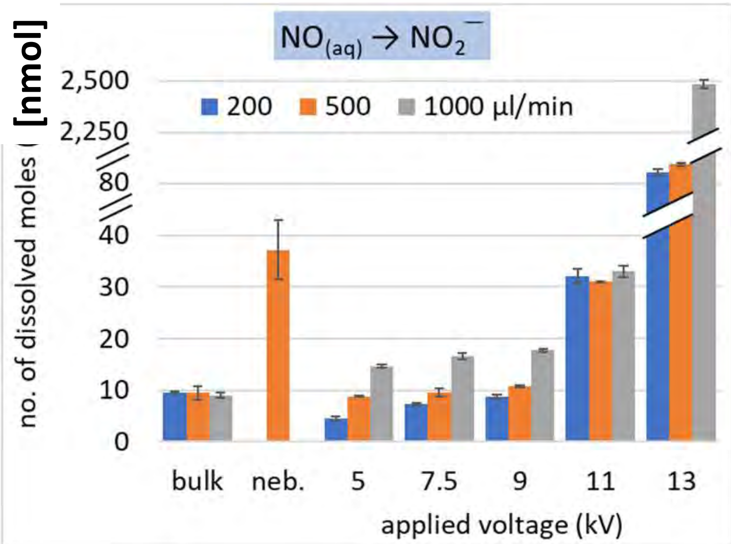




- M.E. Hassan et al., *Water* 2021
- J. Kruszelnicki et al, J. Phys. D: Appl. Phys. 2019

Solvation RNS into water bulk vs. microdroplets

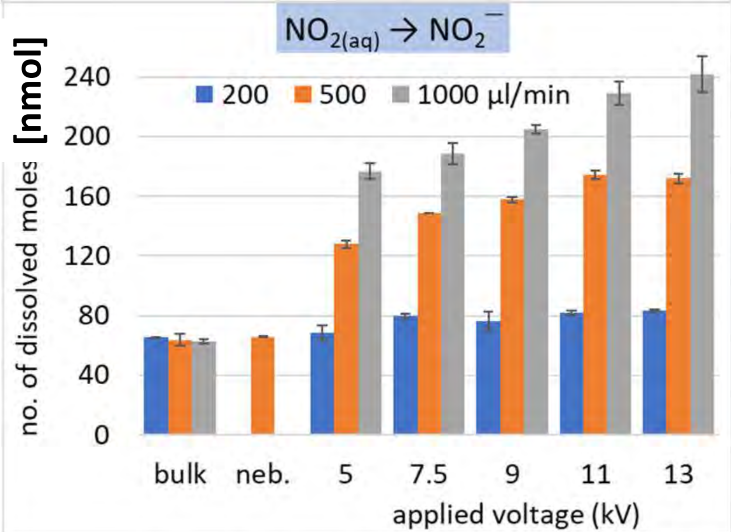
NO



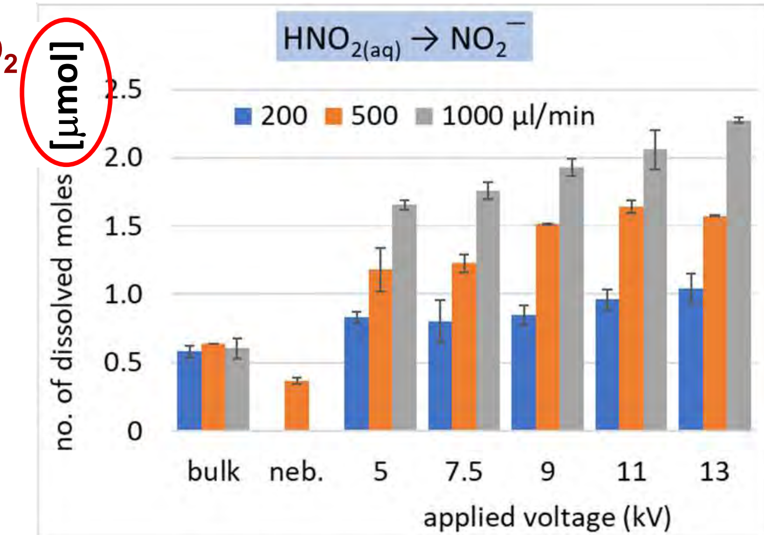
Solvation of

- $(H)NO_x$ is higher than Henry's law – ionize into **NO_2^-** and quickly diffuse in liquid water
- NO is gas – water interface area-dependent - low k_H
- **NO_2** solvation is **charge-dependent** – enhanced in ES, not in nebulizer
- **HNO_2 is a dominant source of NO_2^-** and is **charge-dependent**

NO_2

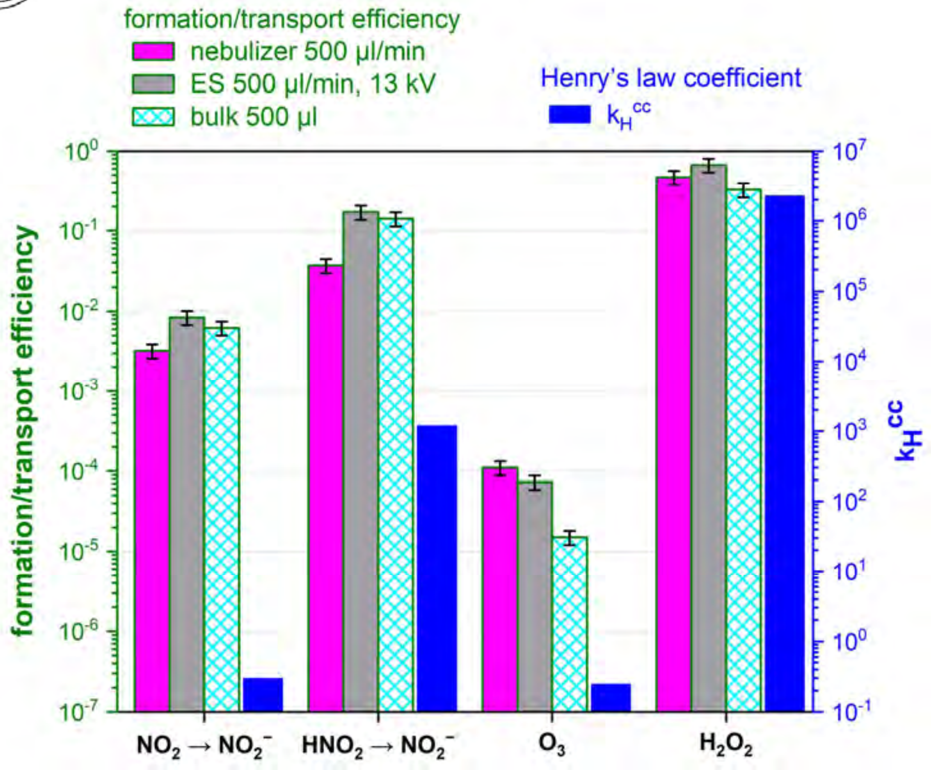


HNO_2

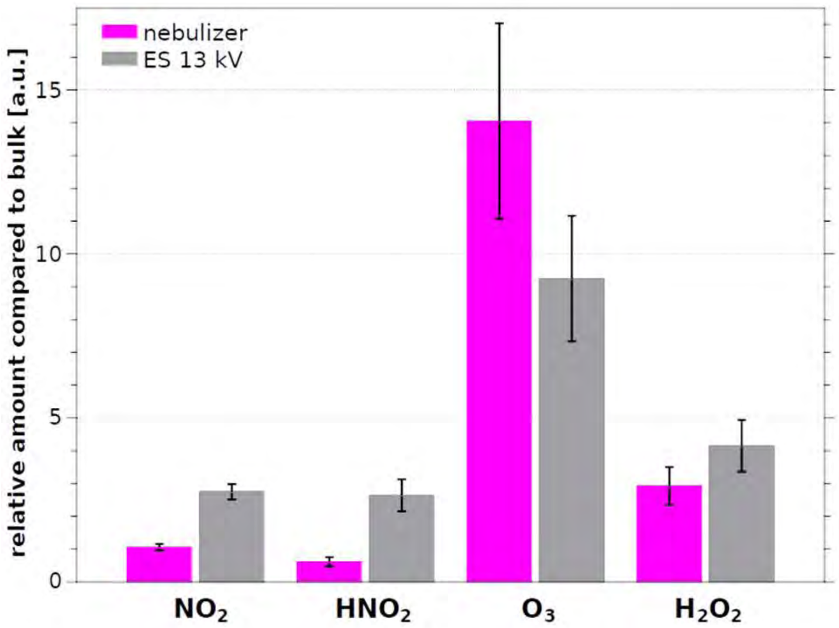


- M. Janda et al., *Appl. Sci.* (2021)
- M. Hassan et al., PCPP (2024)

NO_2^- formation or H_2O_2/O_3 transport efficiencies vs. Henry's law



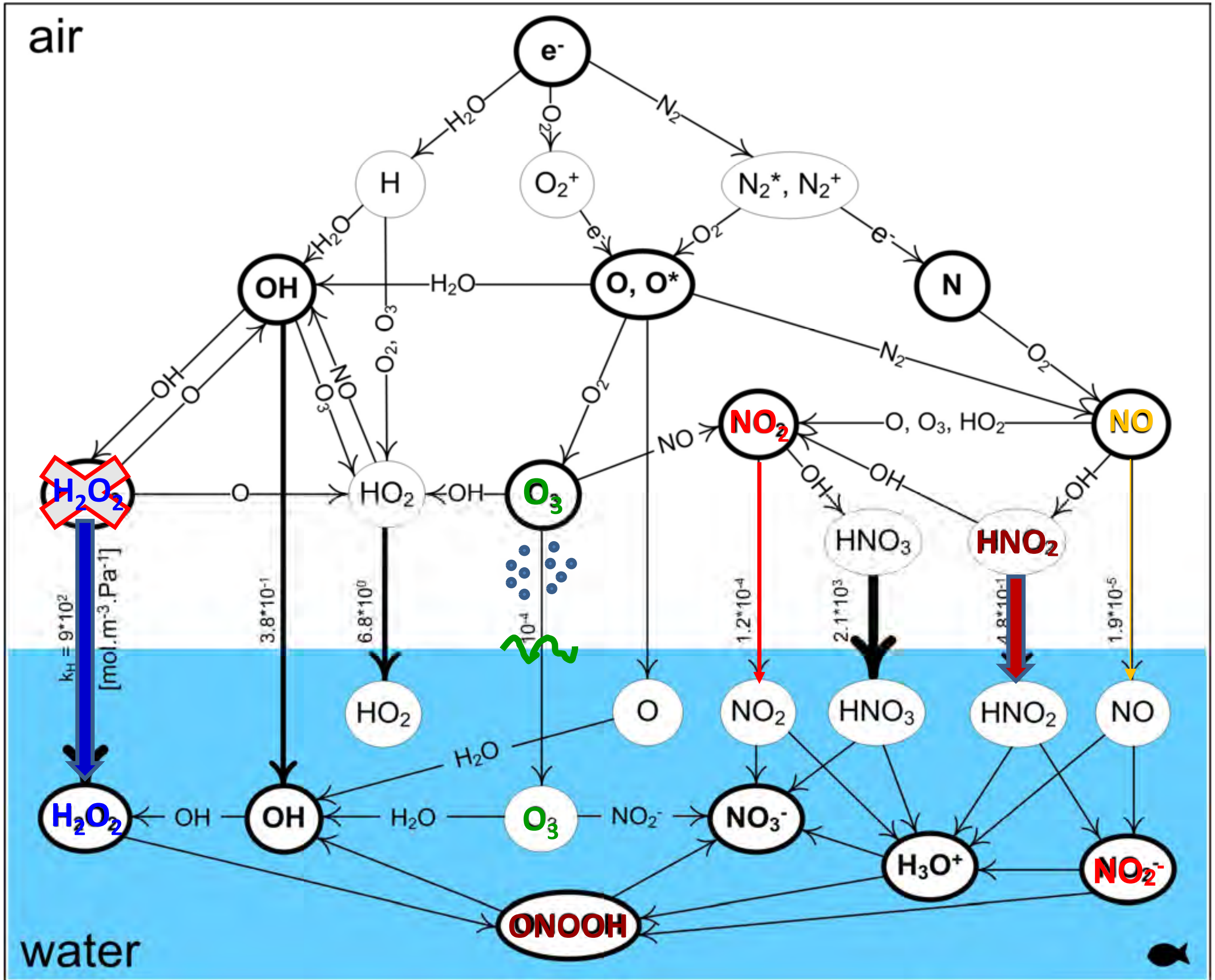
Formation efficiency of NO_2^- from NO_2 and from HNO_2, and the transport efficiency of O_3 and H_2O_2 in the nebulized/ES microdroplets (13 kV, 2 minutes, 500 µl/min), and bulk water (1 minute, 500 µl) with the dimensionless Henry's law coefficients of NO_2, HNO_2, O_3, and H_2O_2.



Relative increase in the molar amount of NO_2^- ions formed from NO_2 or HNO_2, and the solvated O_3 and H_2O_2 in **ES** (13 kV, 2 min, 500 µl/min) and **nebulized microdroplets** (in 2 min, 500 µl/min) **with respect to the bulk water** (1 min, 1000 µl).

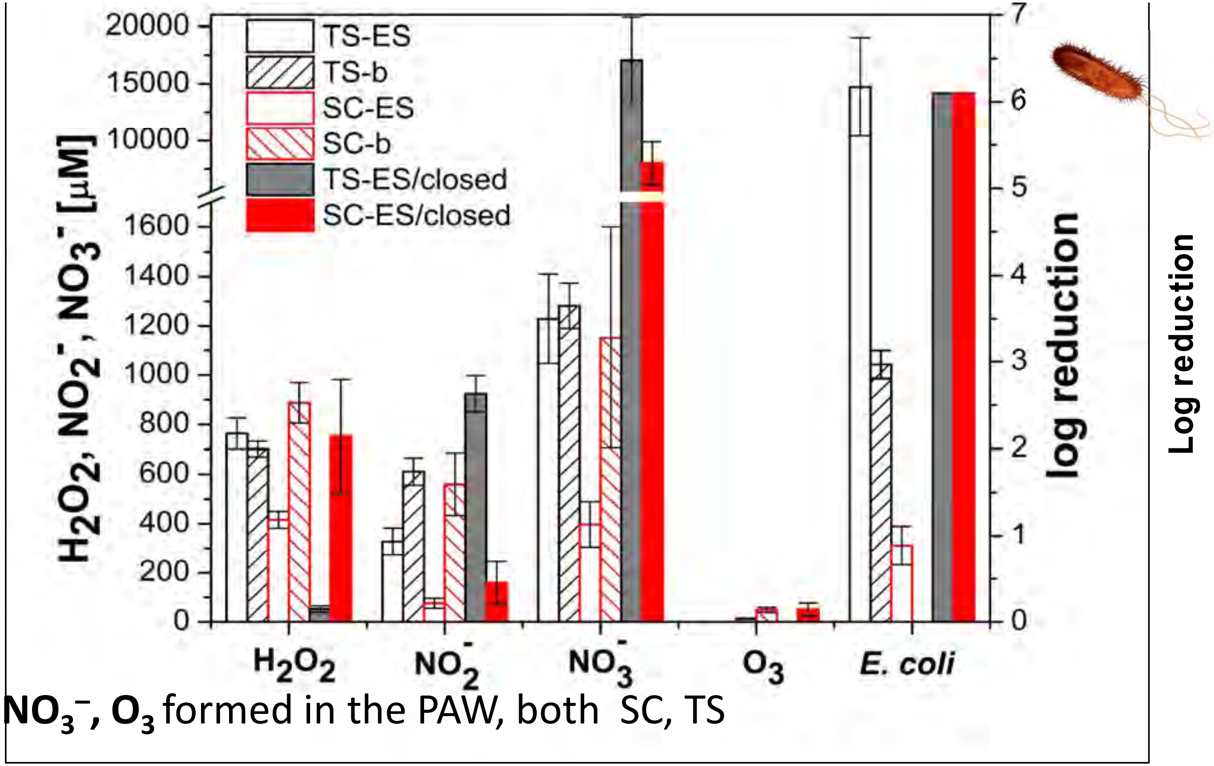
- M.E. Hassan et al., *Plasma Chem. Plasma Proc.* 2024

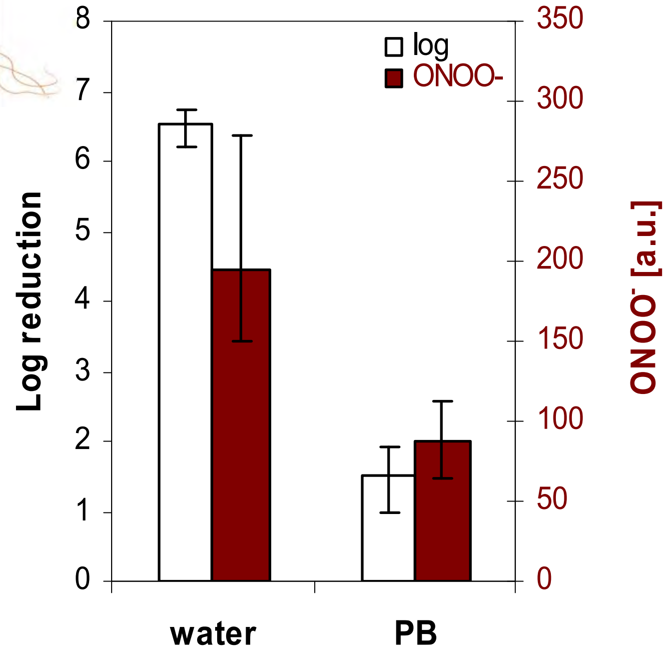
Summary: transport of RONS



- **Transport processes of RONS (**H_2O_2**,** O_3 **and** HNO_2**,** NO_2**, NO)** into bulk water vs. electrosprayed/nebulized microdroplets
  - O_3 solvation depends on gas–water interface area - microdroplets
  - H_2O_2 is very soluble – but **depletion from the gas**
  - **(H)NO$_x$ solvation** – transport is better than Henry's law – effects of charge, liquid $NO_2^-{}_{(aq)}$ ions
  - **HNO_2 is a dominant source of $NO_2^-{}_{(aq)}$**
- Understanding plasma species chemistry and transport → **tuning PAW composition/properties** and specific applications

TS-SC: Aqueous RONS vs. antibacterial effect





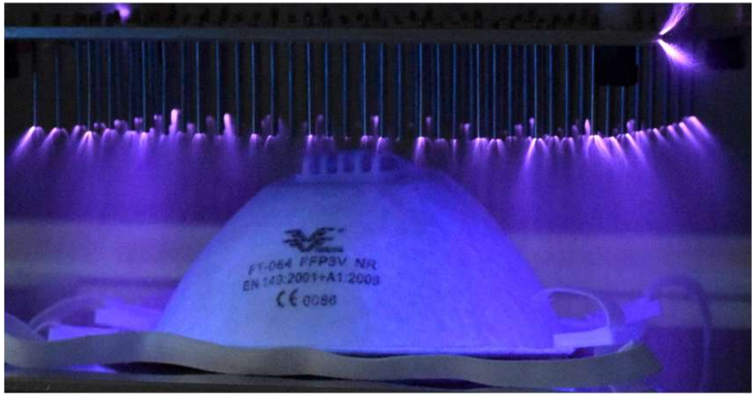
- **H_2O_2, NO_2^-, NO_3^-, O_3** formed in the PAW, both SC, TS
- **PAW composition correlates with the antibacterial effect**:
  - $H_2O_2 + NO_2^- + H^+ \rightarrow$ **ONOOH** $+ H_2O \rightarrow$ **$^{\cdot}OH$** $+ NO_2$ – dominant mechanism in TS (open)
  - **Acidified nitrite**: NO_2^- and NO_3^- in acidic pH - dominates in TS (closed)
  - **Ozone + H_2O_2 rich PAW** - dominates in SC

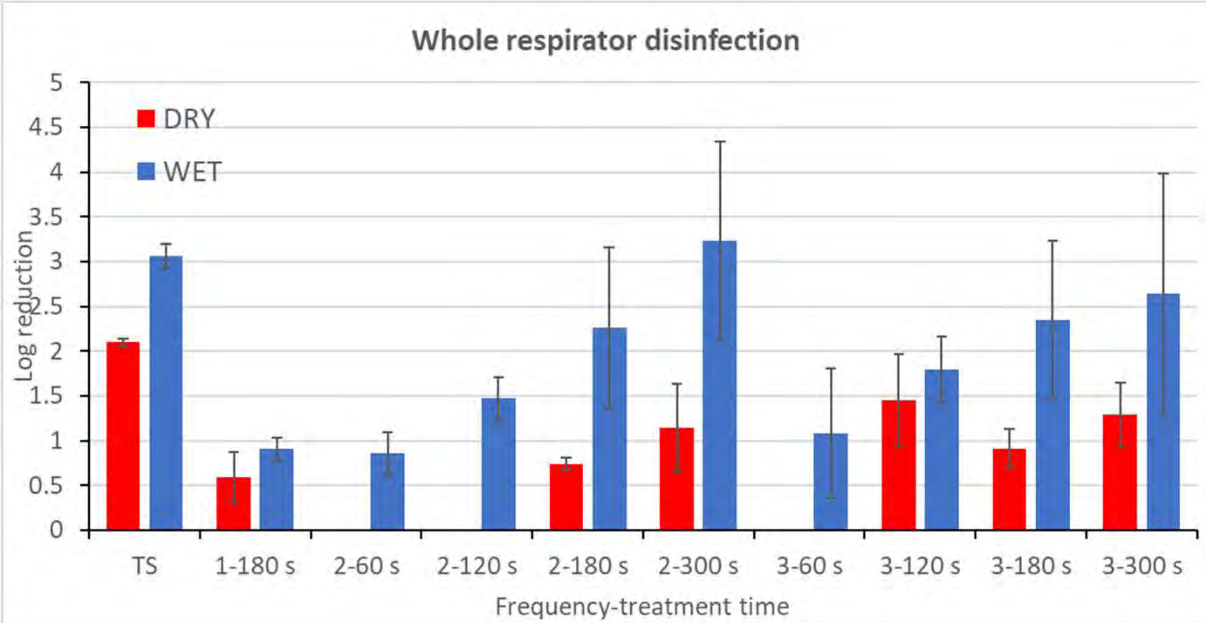
- B. Tarabova et al., *Plasma Proces. Polym.* 2018
- Z. Machala et al., *J Phys. D* 2019
- J. Pawlat et al., *Plas.Chem. Plas. Process.* 2019

Air plasma for respirator disinfection

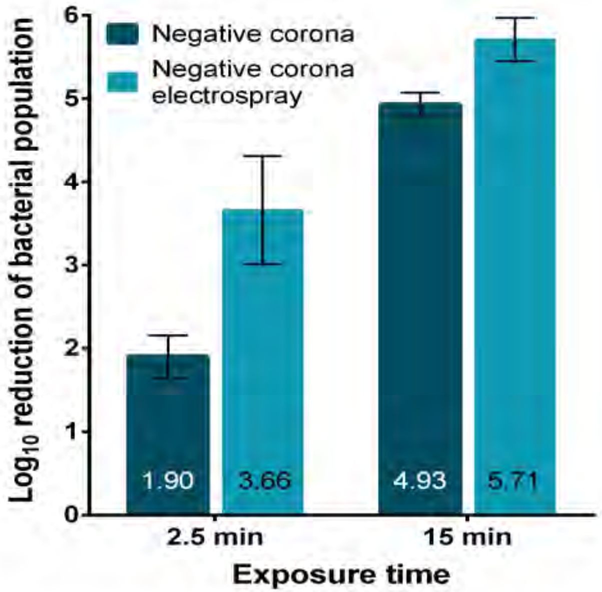
Air plasma against COVID-19:

- air decontamination
- Respirator decontamination by indirect **TS** or **multipin pulsed streamer corona** (tested on sprayed *E. coli* as model pathogen)
- **Wet respirators** show **stronger decontamination effect**



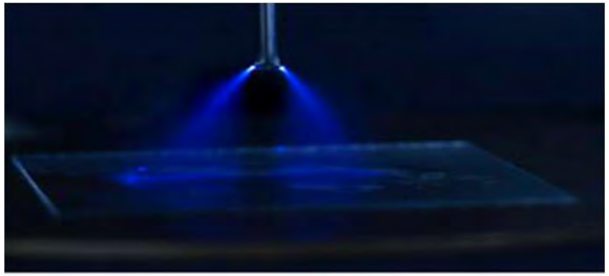


Biofilm decontamination, endodontics



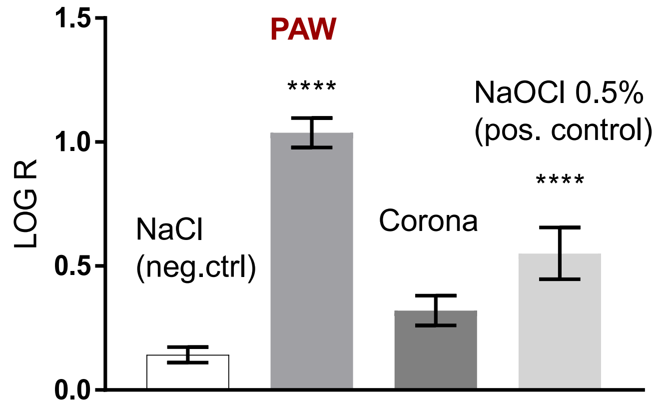
E. coli biofilm on glass

- Up to 2.5-3 logs with water spray (2 min)
- **Water electrospray** strongly **enhanced biofilm inactivation** on teeth, plastic, glass surfaces – from ~1 up to ~3 logs at 2 min
- Chemical effects induced in SC with ES



- Z. Šipoldová et al., *IEEE Trans. Plasma Sci.* 2011
- Z. Kovaľová et al., *Eur. Phys. J. Appl. Phys.* 2013
- Z. Kovaľová et al., *J. Phys. D. Appl. Phys.* 2014
- Z. Kovaľová et al., *Bioelectrochem.* 2016

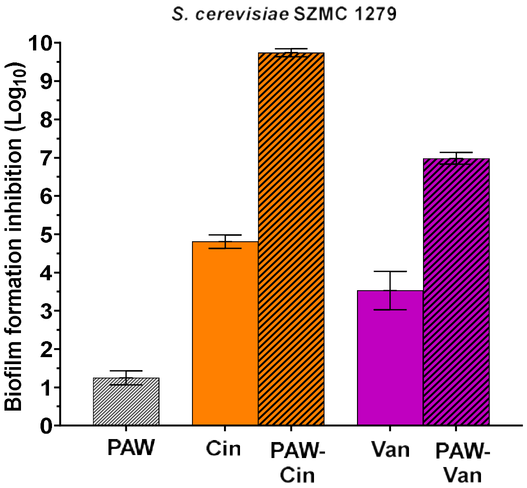
***Ex vivo* teeth (0.5% NaOCl)**

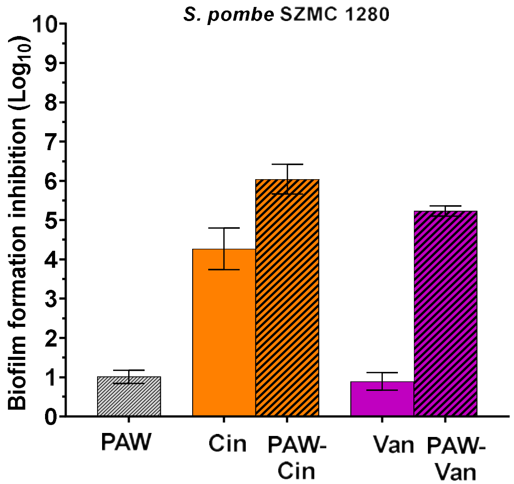


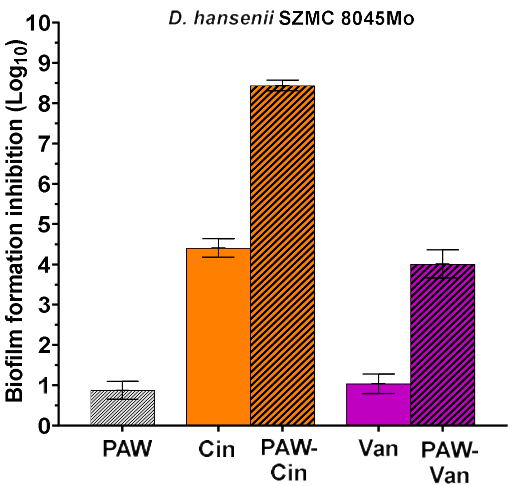
Endodontics

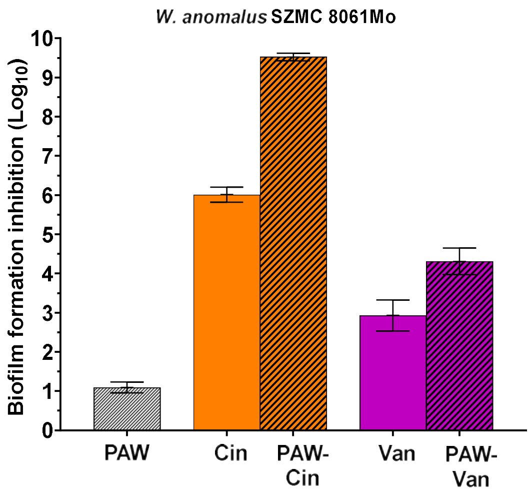
- *E. faecalis* biofilm in tooth root canal
- Saline solution control
- PAW or corona-direct treatment

PAW + phenolics: Biofilm formation inhibition









Phenolics: cinnamic acid, vanillin
concentration=500 µg/mL; 48 h biofilms

- PAW–Cin had the strongest biofilm inhibition across all tested yeast strains
- PAW–Van shows variable efficacy. Effective in *S. pombe* but moderate in *W. anomalus*

D. hansenii

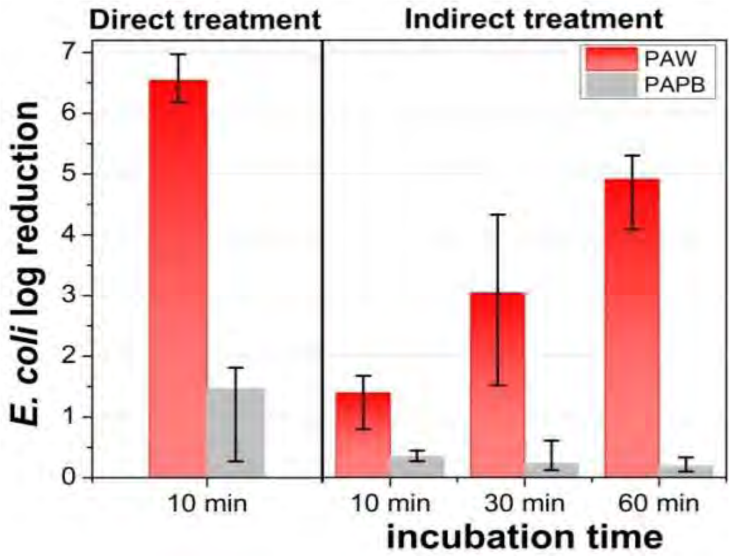
- Halotolerant and osmotolerant
- Thick, multilayered cell wall
- High antioxidant capacity-catalase and glutathione
- Efficient efflux pumps-reduce intracellular toxicity

A synergistic solution against resilient yeasts

Direct TS vs. PAW antibacterial effects

- Antibacterial effects strong in water, weak in buffered solutions
- **Direct TS stronger than PAW** only
- **Electrospray stronger** than batch treatment

- Effect of **short-lived RONS** or **electric field**?



Direct TS-ES vs. **PAW** or PA-phosphate buffer
TS-ES treated 10 min and incubated
with *E. coli* for 10, 30, 60 min at room T

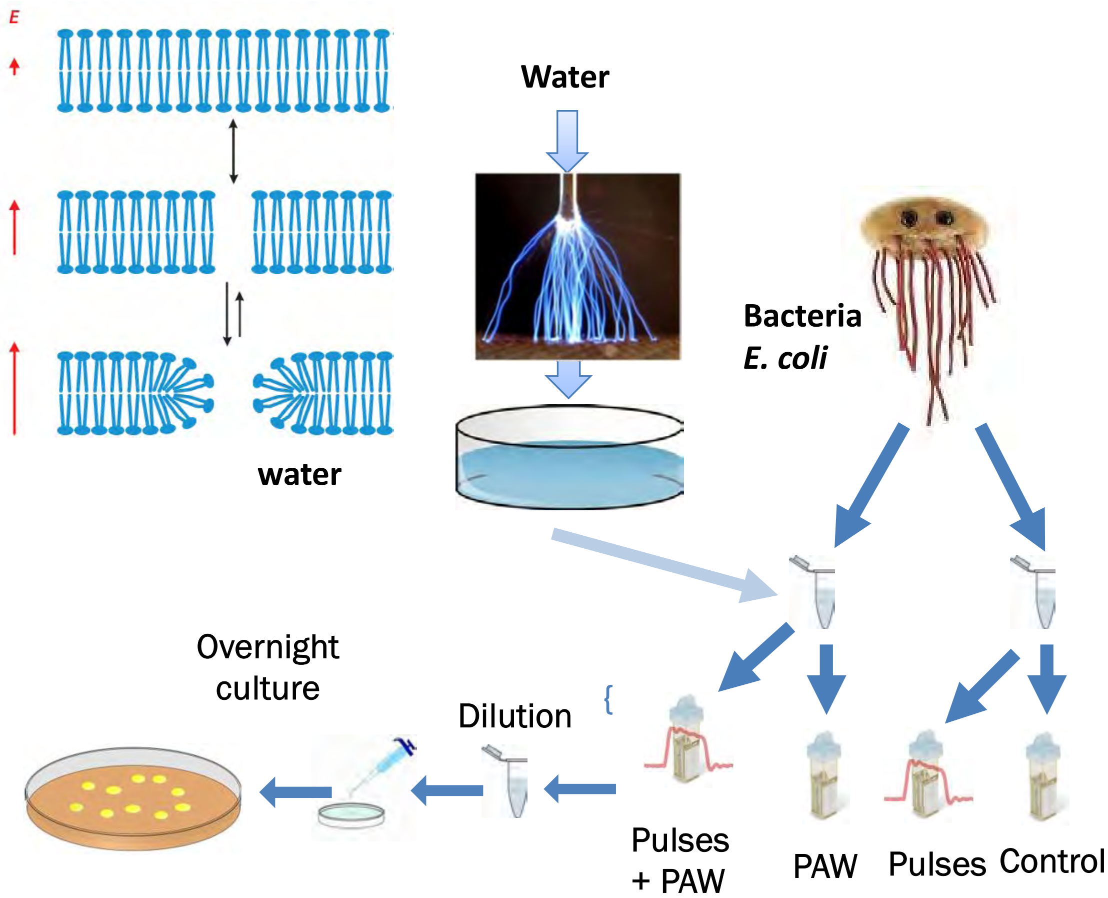
- Antibacterial effect is enhanced by longer incubation in PAW – effect of long-lived RONS or later-induced chemistry

- Z. Machala et al., *J. Phys. D Appl. Phys.* 2010
- Z. Machala et al., *Plasma Proc. Polym.* 2013

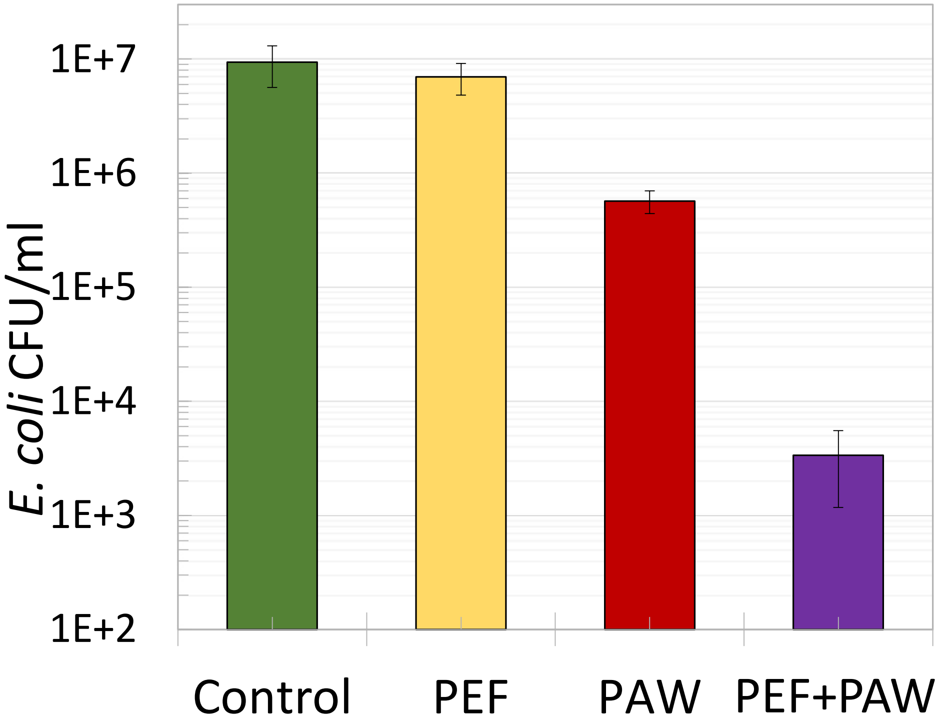
Combined effect of PAW and pulsed electric field

Effect of electric field

Electropermeabilization combined with RONS in PAW – enhanced



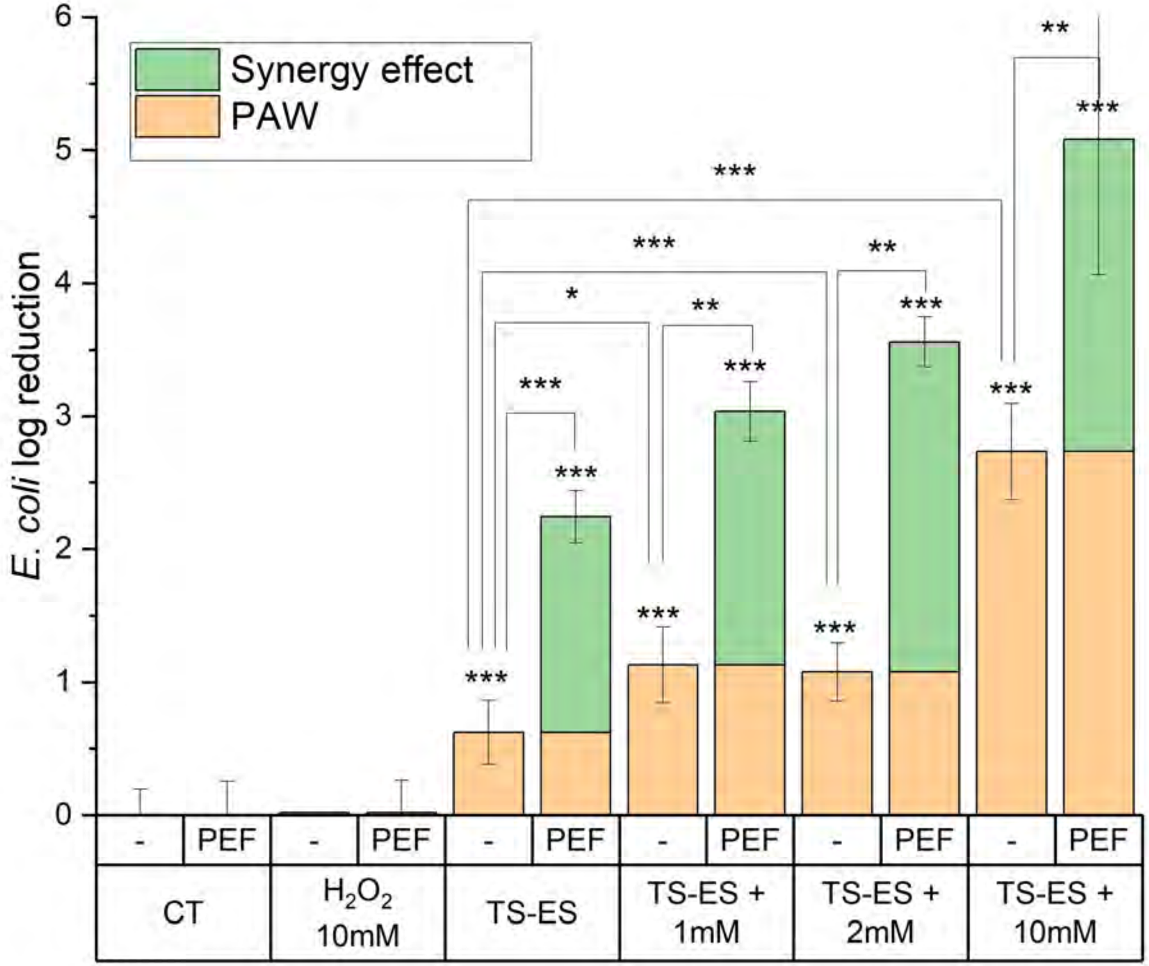
200ns Pulses 1kHz; 10s; 12.5kV/cm;
15min incubation



- R. Mentheour & Z. Machala, *Front. Phys.* 2022

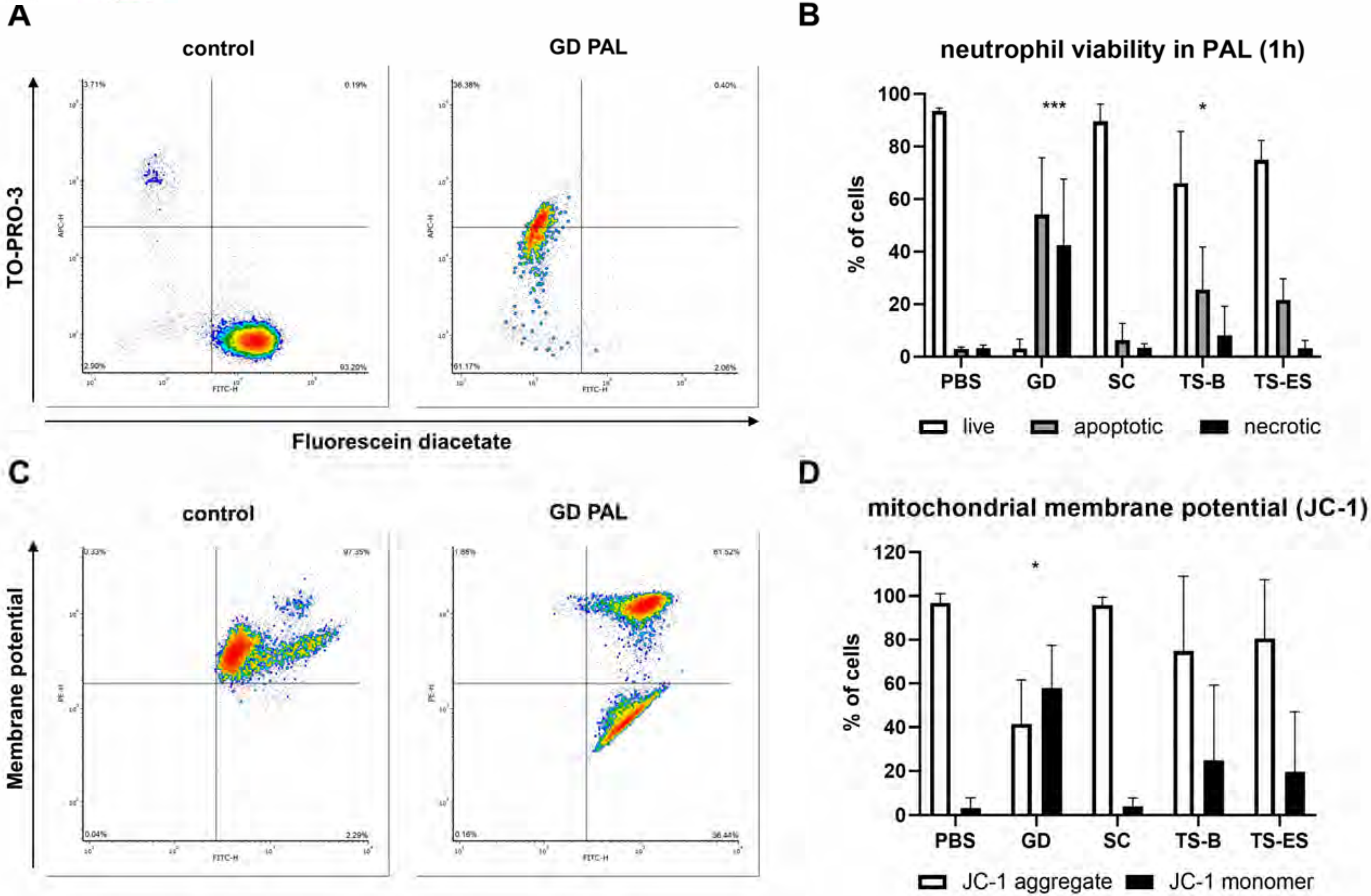
PAW+ pulsed electric field synergic antibacterial effect

- PEF treatment only: no antibacterial effect
- H_2O_2 only: no antibacterial effect
- **Open air TS-ES PAW + PEF**: **synergy effect** thanks to both H_2O_2 and NO_2^-
- $H_2O_2 + NO_2^- + H^+ \rightarrow$ **O=NOOH** $+ H_2O \rightarrow$ **$^{\bullet}OH$** + **$NO_2\cdot$** $+ H_2O$
- Antibacterial effect and synergy increased with adding H_2O_2



- R. Mentheour & Z. Machala, *Front. Phys.* (2022)

PAL effect on neutrophils (*in vitro*)



Neutrophils (white blood cells) have strong role in combating infections *in vivo*

- Induce NET-osis

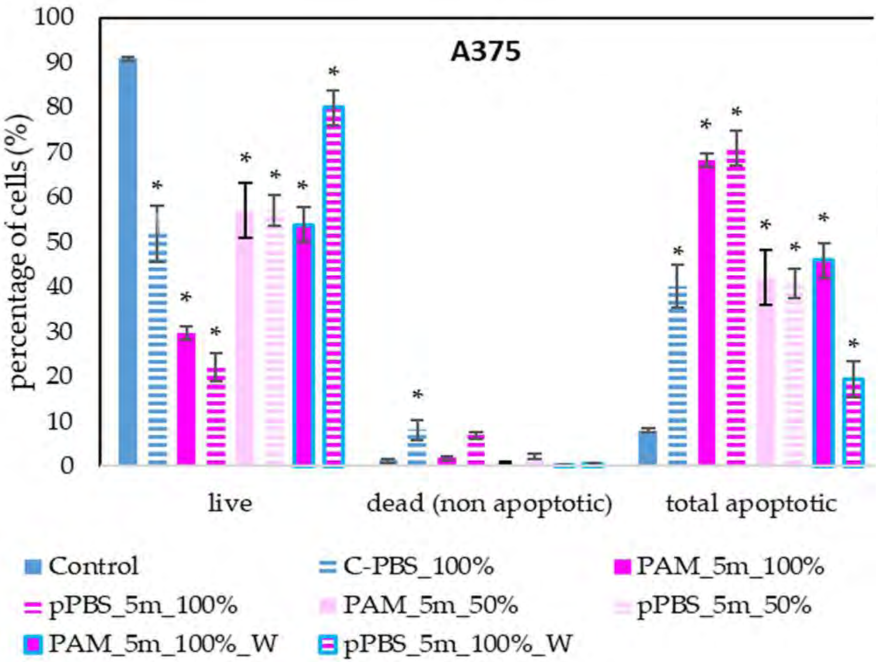
Flow cytometry
→ **neutrophils are affected by PAL (GD)**

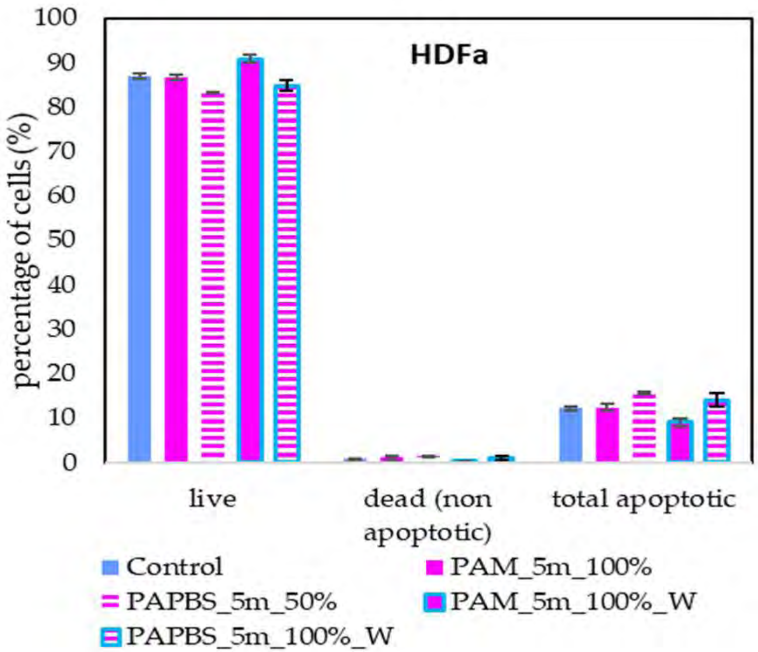
- M. Pastorek, et al. *Plasma Chem. Plasma Process.* 2022

Cancer cell apoptosis induction by PAM/PAPBS

- **Human melanoma epithelial cancer cells A375, normal human fibroblasts HDFa,** Muse® Annexin V & Dead Cell Kit – flow cytometry
- Streamer corona treatment of cell culture medium or PBS, 5 min, 12.8 kV, 1 cm, 5 ml
- 50% diluted or 100% PAM/PAPBS, **W**-washed after 30 min of incubation in PAM/PAPBS

Collaboration with H. Gbelcová, V. Repiska Faculty of Medicine, Comenius Univ. Bratislava

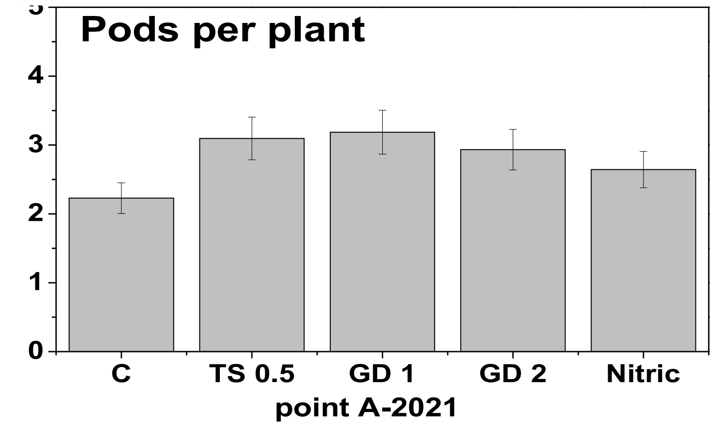


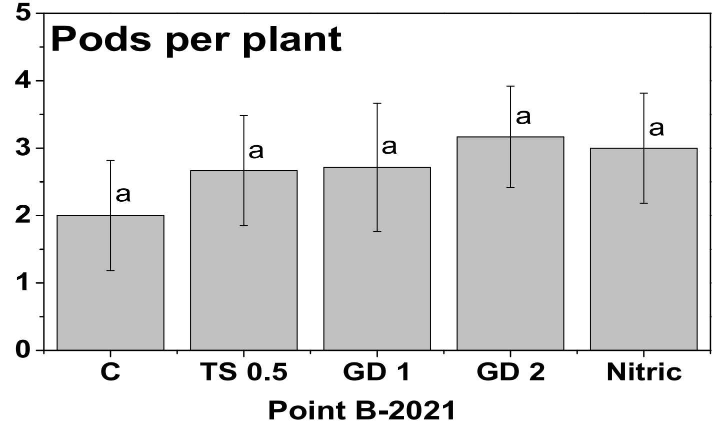


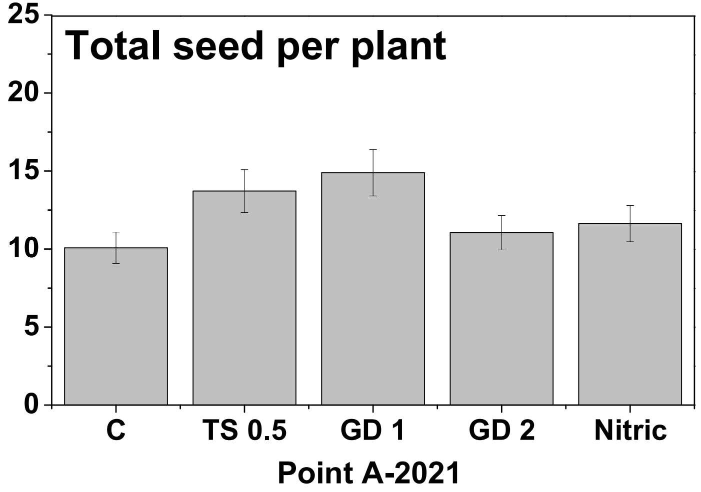
- **PAM and PAPBS** reduced cancer cell viability and caused **apoptosis**, even after washing – **no apoptosis in normal cells!**

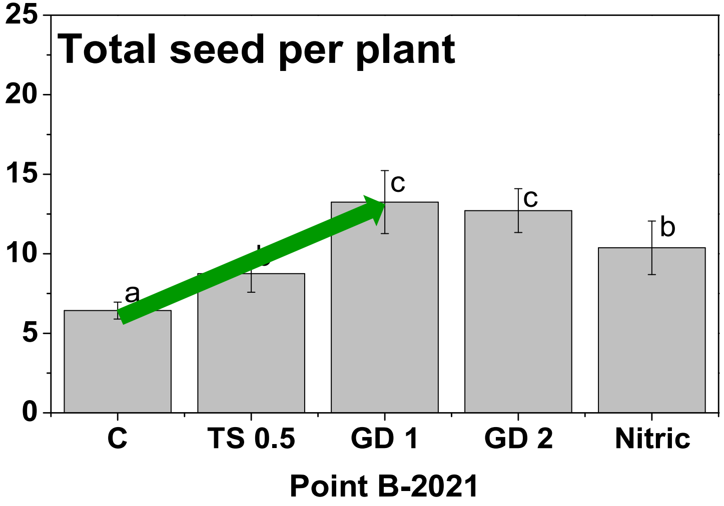
- D. Sersenova et al., *Molecules* 2021

Outdoor field planting: PAW-priming enhanced pea yield









Pods and total seeds per plant, point A-2021 and point B-2021.

C – control, plasma: TS-0.5, GD 1, GD 2, and Nitric (pos. ctrl.)

Pea (*Pisum sativum* L. cv. Eso)

Collaboration with R. Švubová, D. Kostoláni, S. Kyzek
Faculty of Natural Sciences, Comenius Univ. Bratislava

- G.B.Ndiffo Yemeli et al., *Plasma Chem. Plasma Proces.* 2022

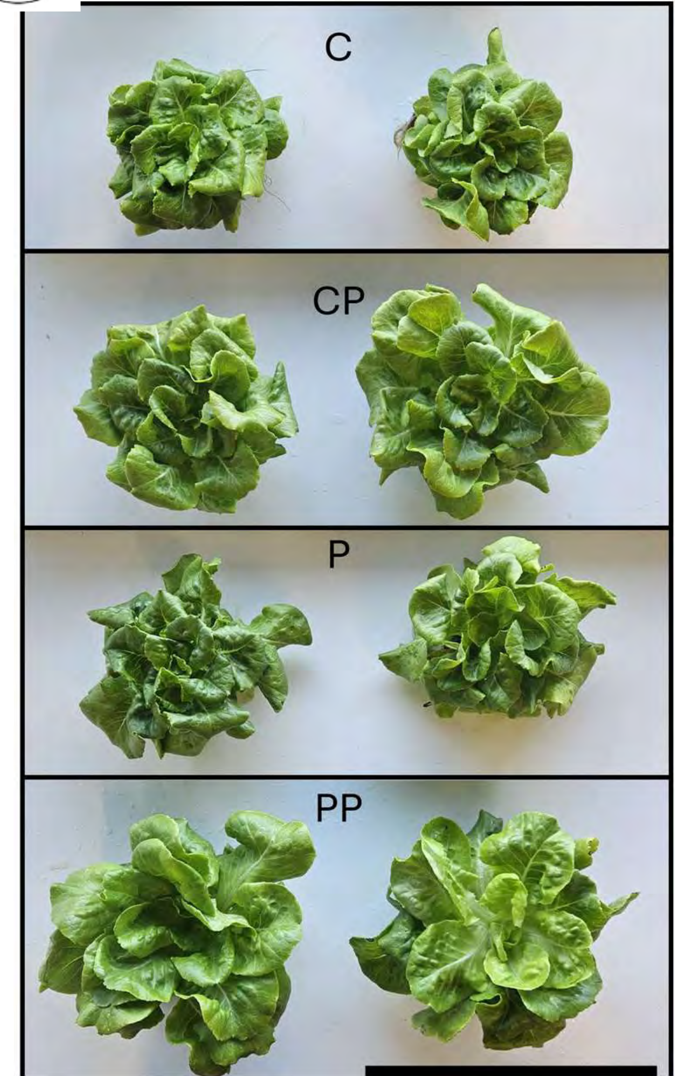
Hydroponic cultivation in PAW - lettuce

Treatment groups:
- **C- control** (1/2 Hoagland nutrient solution, pH 6.2)
- **CP – control + seed priming in PAW** 1.5h, cultivation in ½ Hoagland solution)
- **P - cultivation in TS multineedle PAW** mixed with ½ Hoagland
- **PP – PAW + seed priming**

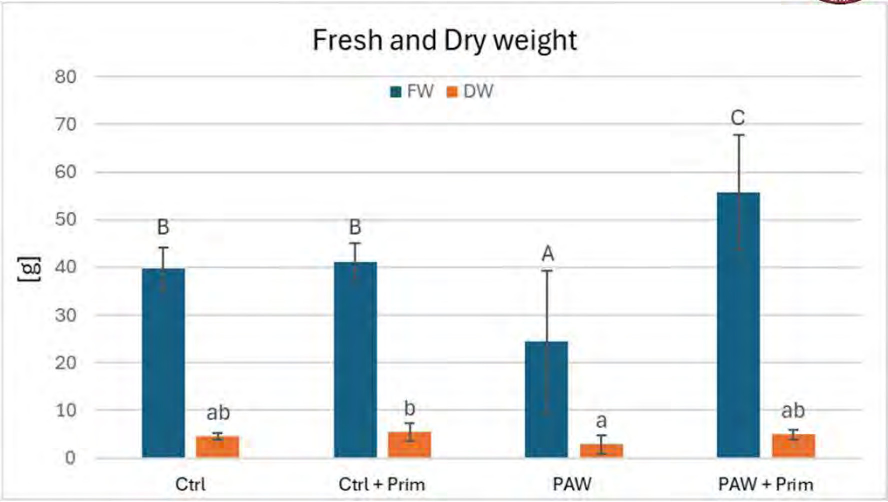
Hydroponic cultivation: 10 weeks
- **Lettuce** *Lactuca sativa* (hybrid Cassini)
- Vertical columns, horizontal systems
- Hoagland and PAW+Hoagland exchanged every week – based on the progressive decay of H202, NO2- and NO3- were stable
- Solutions were aerated during cultivation
- During the 1st 4 weeks – red/blue light
- Then 16h /8 h white light/dark period
- Light intensity PAR : 250 µmol.m^{-2}.s^{-1}
- T=23°C

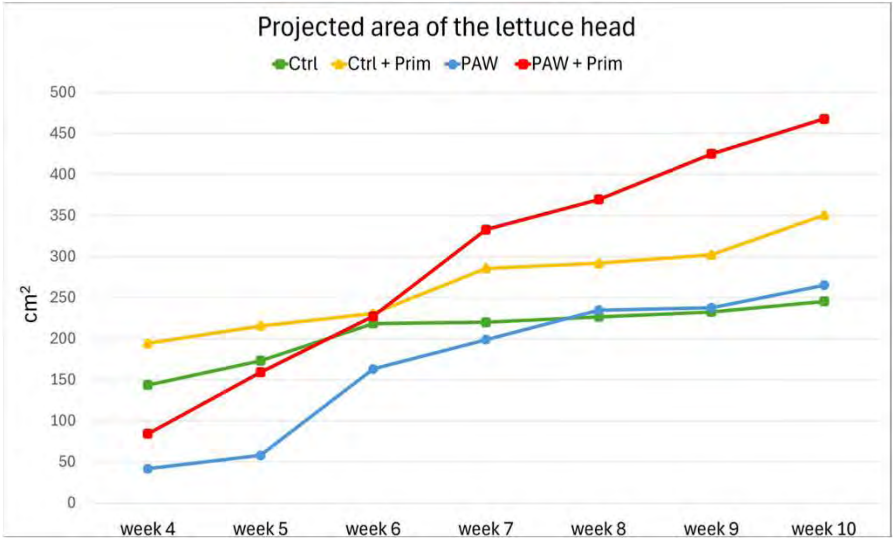
- R. Mehrabifard et al., *Plasma Proces. Polym.* 2025

Hydroponic cultivation – PAW enhanced lettuce



- **PAW+ Priming** - the largest fresh leaf area by weight
- PAW - the smallest fresh leaf area
- **PAW+priming** leaves contained more water – juicier – which corresponds to the sensoric test.

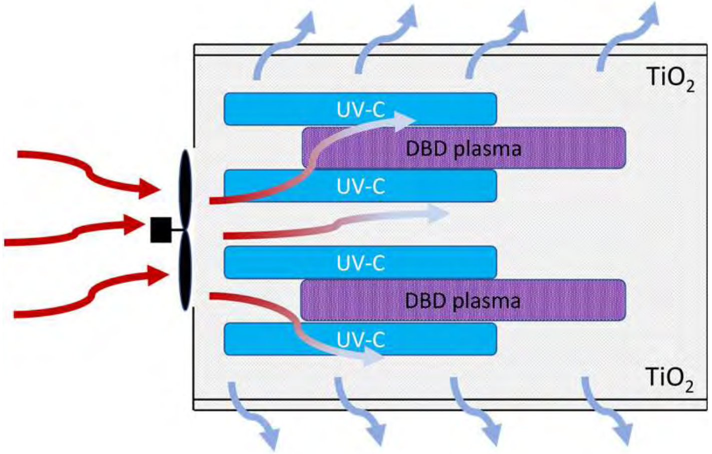


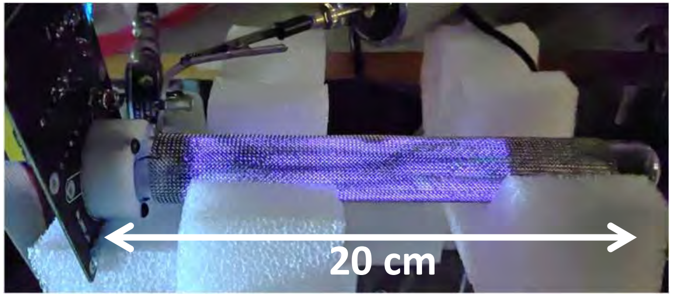


Indoor air decontamination by DBD combined with TiO_2 photocatalysis - system 1

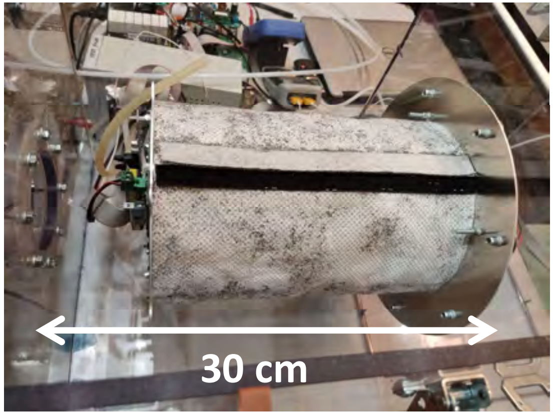
System 1:

- 2 DBD tubes
- 4 UV-C lamps (Hg, 254 nm)
- Low plasma power ~ 30 W (AC ~25 kHz)
- Gas flow rate = 100-650 L/min
- Specific Input Energy (SIE) of DBD = 3 J/L





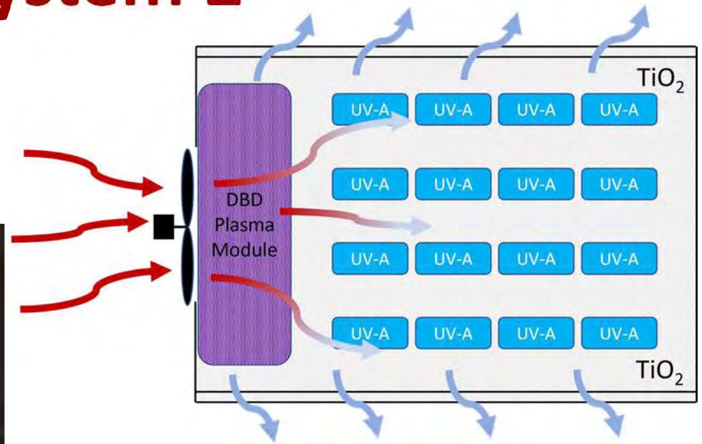
DBD tube



System 1 with TiO_2 layer

- T. Vazquez et al., J. Electrostat. 2025

Indoor air decontamination by DBD combined with TiO_2 photocatalysis - system 2



System 2:

- DBD module (direct treatment)
- 16 UV-A LEDs (370 nm)
- Higher plasma power ~ 20-130 W (AC power supply 40-61 kHz)
- Gas flow rate = 100-650 L/min
- SIE = 2 - 12 J/L

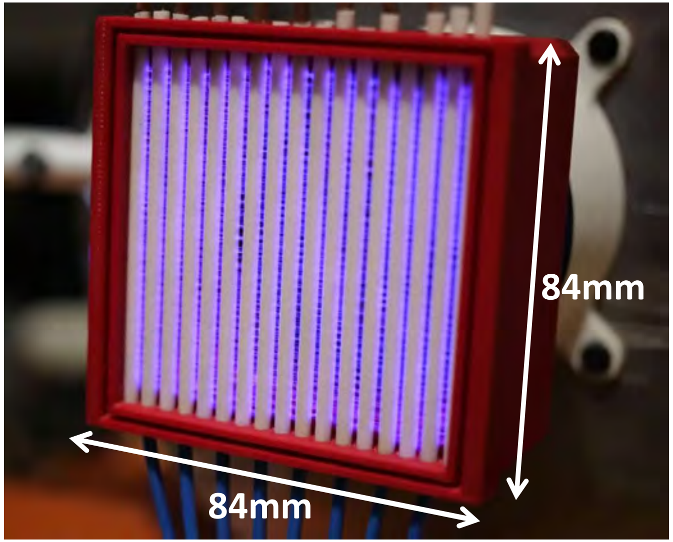
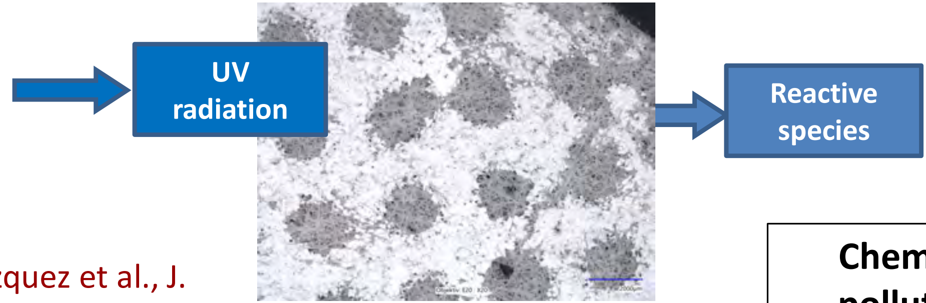


Photo of the DBD module

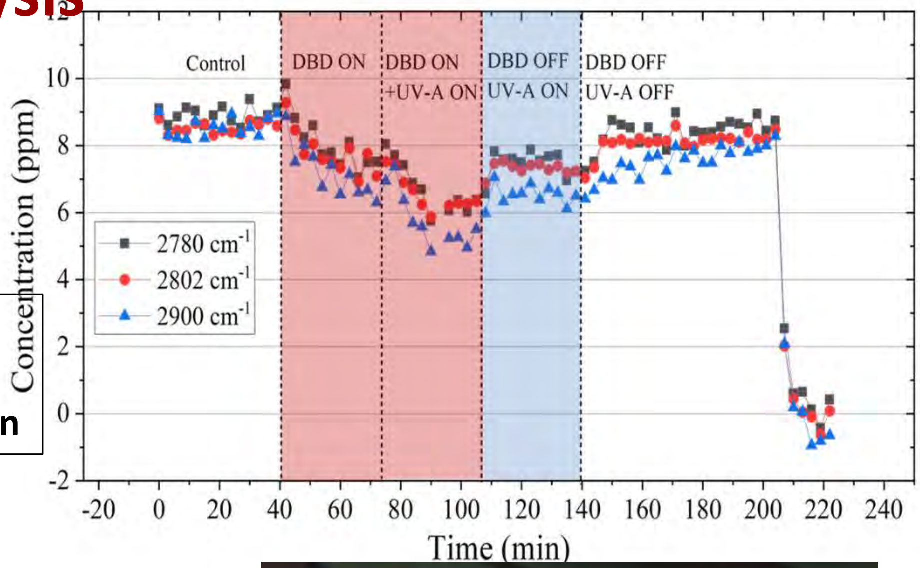
- T. Vazquez et al., J. Electrostat. 2025

Indoor air decontamination by DBD combined with TiO_2 photocatalysis

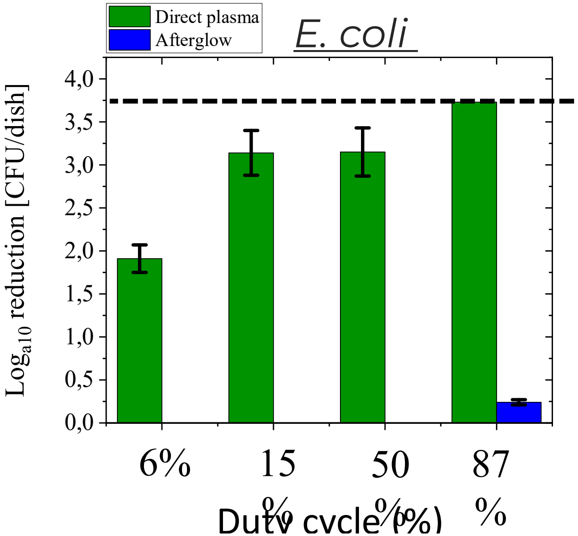


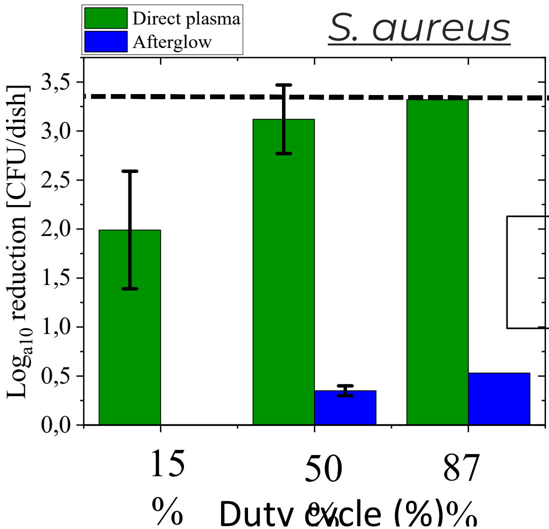
TiO_2 layer

Chemical pollutant decomposition



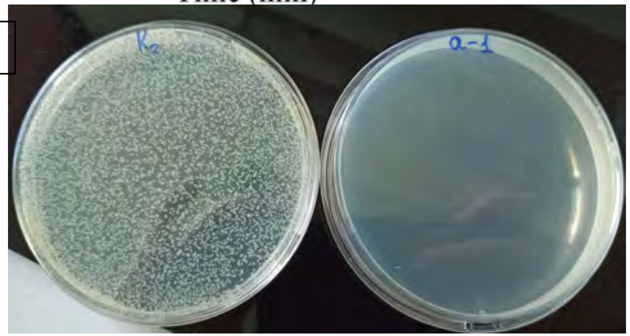
- T. Vazquez et al., J. Electrostat. 2025





100% inactivation

Bacteria inactivation



Bio-aerosols containing *E. coli* collected during 60s. Left: control, Right: plasma treated, 87%

Summary

- **Plasma-liquid interactions** are driven by the transport of reactive species into liquid
- Air plasma discharges: O_3 vs. NOx mode
- **Transport processes of RONS** (**H_2O_2**, **O_3** and **HNO_2**, **NO_2**, NO) **-** bulk water vs. electrosprayed/nebulized microdroplets
- **Diagnostics of RONS in gas and liquid**
- Understanding plasma species chemistry and transport into water → **tuning PAW properties for applications**
- PAW effects depend on PAW chemistry and synergize with the electric field

Examples of our wastewater/bio/agro applications:

- **Organic dye degradation**
- **Biofilm eradication, dentistry, wound healing, cancer treatment**
- Effects on **plant growth enhancement** depend on PAW composition
- Indoor air decontamination by DBD plasma + TiO_2 photocatalysis