terraplasma

whitepaper

Introduction to CAP
(cold atmospheric plasma)

about us

terraplasma GmbH is a global leader in the research, development and productization of cold atmospheric plasma (CAP) solutions.

terraplasma GmbH was founded in 2011 as a spin-off of the world-renowned Max-Planck Society to commercialize three decades of cold-plasma research.

We see cold atmospheric plasma as a platform technology with a wide range of potential applications, and our strategy is to develop a variety of stable plasma systems and transfer technologies which can be easily and cost-effectively tailored to specific industries and applications.

Over the past decade, terraplasma has developed numerous products in the fields of skincare and wound-treatment, disinfection and sterilization and for the removal of odors and allergens, both with leading partners and as standalone products. terraplasma GmbH and its partners have sold >35,000 products which incorporate terraplasma`s patented technology.

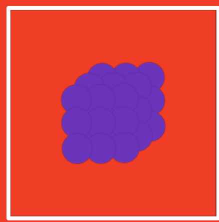
terraplasma was founded by the world-renowned physicist Prof. Dr. Gregor Morfill and Dr. Julia Zimmermann.

what is plasma?

When energy (in the form of heat) is applied to a solid substance (e.g. ice), the substance undergoes a phase change, as illustrated in the stages below.

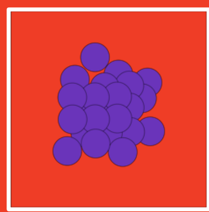
Solid

Molecules in the solid state are usually highly ordered (crystalline). On heating there is a phase change at a specific temperature – the melting point – where the substance (ice) becomes → liquid



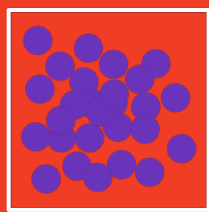
Liquid

This phase is less ordered, but there is still some correlation between the molecules. On further heating the liquid state undergoes another phase change → gas



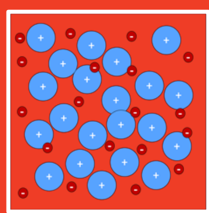
Gaseous

In this phase the molecules are highly disordered and the thermal energy is greater than the intra-molecular binding potential. With atomic gases, the next phase transition is directly into the → plasma phase.



Plasma

In the case of a molecular gas, there is an intermediary stage. Further heating first results in dissociation and the breaking up of the molecules into their atomic constituents (hydrogen and oxygen) – until eventually the atomic phase is reached (H and O).
Additional heating then results in the atoms becoming ionized (H+,O+ and e-) – the collisions are sufficiently energized to remove electrons from the atoms, leaving a mix of negatively charged electrons and positively charged ions. The system is overall charge neutral – a plasma.



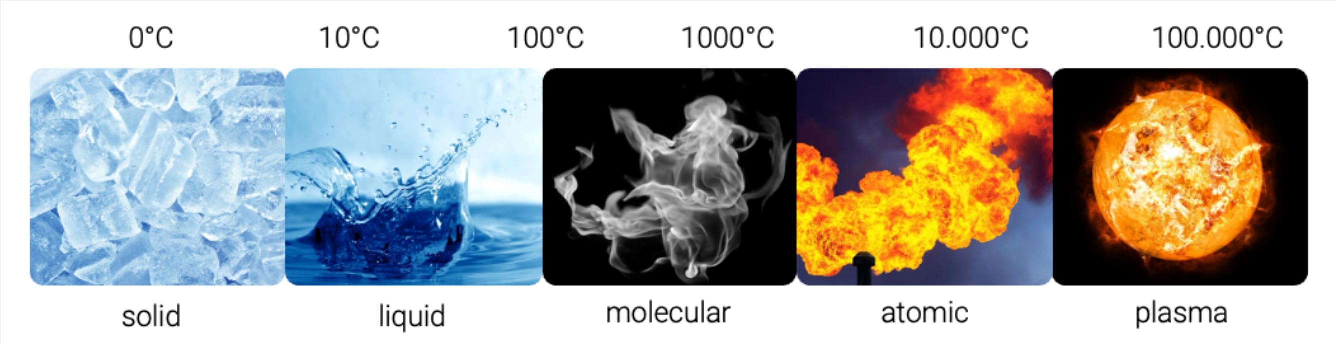


Figure 1: The various states of matter, illustrated with H_2O – from ice, to water, to steam, to atomic and finally to plasma.

Plasma (in our sun) is essentially the matter which allows life on Earth to exist, providing us with nearly unlimited light and energy. The ultimate source of this energy is proton-proton fusion in the core of the sun, with temperatures reaching about 15 million °C. The pressure of this hot gas is counterbalanced by the self-gravity of the sun – thus the hot gases remain confined.

The overall process of fusion within the Sun proceeds from proton-proton interactions to Helium-4 (^{4}He) formation. The mass difference between 4 protons and one ^{4}He is emitted in the form of radiation – about 3.8 x 10^{26} joules of energy per second. To put this into perspective, the sun produces about half a million times the energy per second, which humanity expended in all of 2023.

As the images above demonstrate, the plasma phase represents the hottest and most disordered stage (further application of heat will eventually liberate a whole range of elementary particles, but this leads us into elementary particle physics - an entirely different topic).

Electrons and ions will eventually recombine to form a neutral particle (with the emission of excess energy in the form of light). Therefore, to sustain a plasma, energy must be continuously applied.

plasma is the most abundant form of matter in the universe - accounting for over 99% of the visible matter (e.g. stars and the interstellar and intergalactic medium).

what is cold plasma?

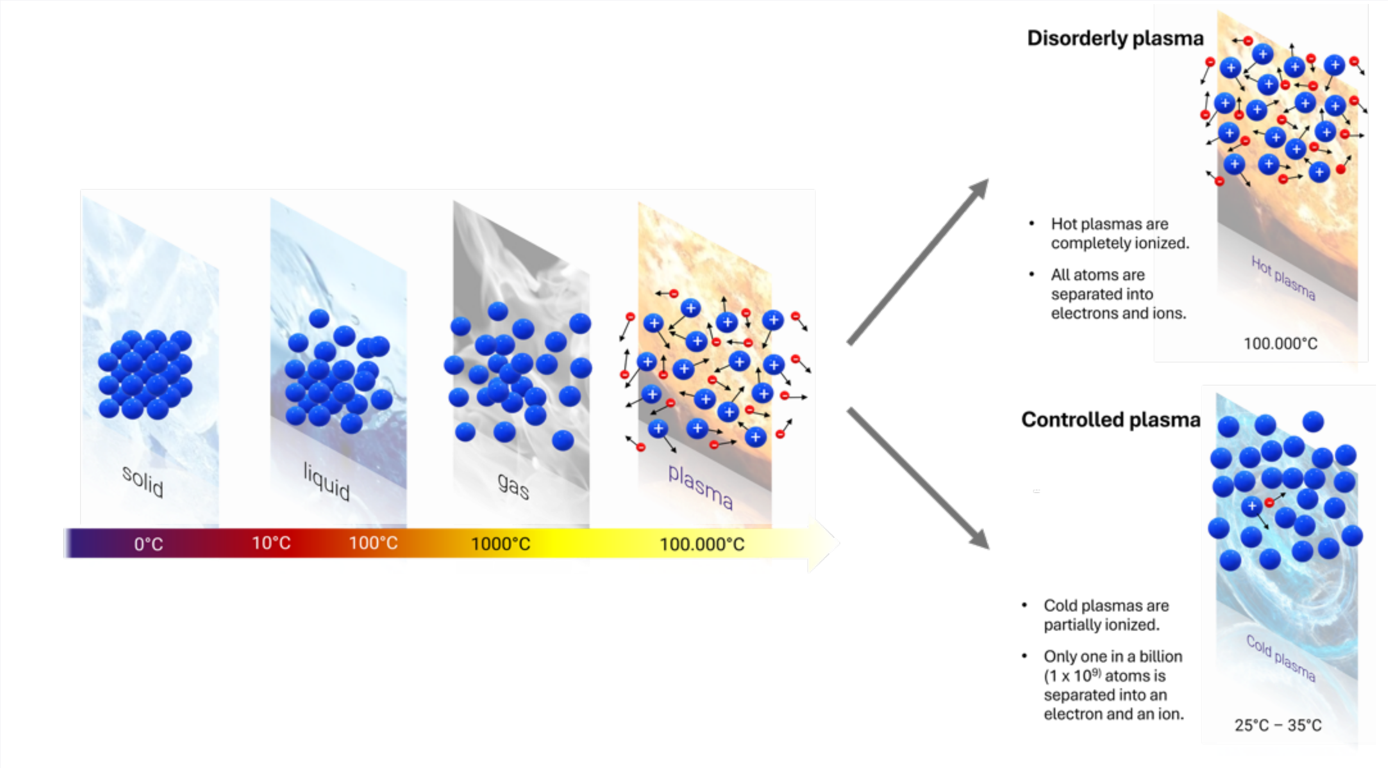


Figure 2: An overview of the uncontrolled process of hot vs. controlled cold plasma, initially produced at the Max- Planck Institute and further developed by terraplasma GmbH.

In contrast to hot plasma, cold plasma operates at or just above room temperature, raising the question – how is this possible, when plasma is the hottest normal state of matter?

Cold plasma is created when a gas is supplied with just enough energy to ionize only a few of its particles, in contrast the disorder and thermally active nature of plasmas. This cold plasma particle mixture - called a “plasma cocktail” - can be used in water treatment, the food industry, but also in medicine and healthcare.

At the time of formation, the ions and electrons are extremely hot (typically around 100.000 K). The rest of the neutral gas, from which they were formed, remains at room temperature (about 23°C, or 296 K). It is simple to calculate that a 10^{-4} degree of ionization (i.e. 1 in 10.000) will increase the average temperature by 10K, from 296 to 306 K. Similarly, a more typical degree of ionization of a cold plasma – in the range 10^{-8} to 10^{-10} – will have practically no effect on the average temperature.

By carefully controlling the conditions of ionization, plasma can be generated and harnessed for a variety of medical, industrial, and technological applications.

generating cold plasma.

There are several ways to generate cold plasma, and depending on the technical design, several technology concepts can be distinguished (surface micro discharge, dielectric barrier discharge, plasma jet, etc.). What they all have in common is that at least two electrodes (an electrically conductive material) and an electrical insulator are arranged in a specific way.

When an electrical voltage is applied, tiny flashes occur directly on the surface of the plasma source, creating the plasma cocktail. Each of the technologies listed above has advantages and disadvantages, which determine the suitability for specific applications (e.g., wound treatment, sterilization, water treatment, etc.) and the corresponding technical specifications.

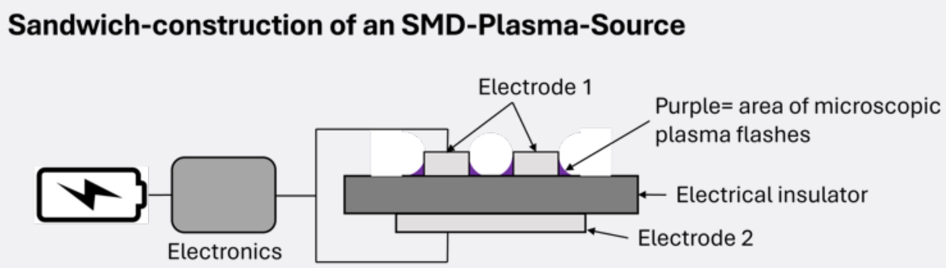


Figure 3: Sandwich construction of an SMD plasma source developed by terraplasma GmbH.

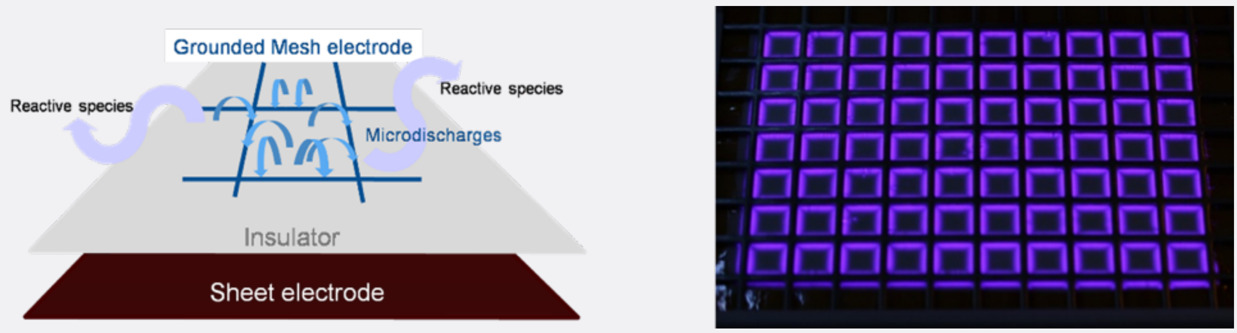


Figure 4: Schematic of an SMD electrode creating micro-discharges and the production of reactive species (left), image of SMD electrode in an activated state (right). The purple glow are the micro-discharges, best observed in dark conditions.

Ions and electrons

N^+, N_2^+, N_3^+, N_4^+, O^+, O_2^+, NO^+, NO_2^+, H^+, H_2^+, H_3^+, OH^+, H_2O^+, H_3O^+, e^-, O^-, O_2^-, O_3^-, O_4^-, NO^-, N_2O^-, NO_2^-, NO_3^-, H^-, OH

Reactive species

excited N_2, excited O, H, N, O, excited O_2, O_3, NO, N_2O, NO_2, N_2O_3, N_2O_4, N_2O_5, H_2, OH, HO_2, H_2O_2, HNO, HNO_2, HNO_3

Figure 5: Partial overview of ions and electrons, as well as reactive species produced by terraplasma's skin treatment SMD plasma source.

↘ some properties of cold plasma

It is instructive to summarize some typical parameters of cold plasmas. Of course, this depends very much on the plasma source, so here we will focus on one particular (and common) type of source – the DBD (Dielectric Barrier Discharges) or SMD (Surface Micro-Discharges) source, which share many similarities. In both sources the plasma is produced in millions of micro-discharges. This is achieved by introducing a dielectric barrier between the electrodes, thus retarding the formation of a continuous discharge. This idea dates back to Theodore du Moncel (1855) and Werner von Siemens (1857). Depending somewhat on the geometry and operating parameters, these micro-discharges have the following typical properties at atmospheric temperature and pressure:

- Lifetime 1 – 20 nsec
- Filament radius 50 – 200 µm
- Filament length 1 – 2 mm
- Peak current ~100 mA
- Electron density 10^{14} – 10^{15} cm^{-3}
- Electron energy 1 – 10 eV
- Dissipated energy ~ 5 µJ

Both SMD and DBD cold plasma sources can be configured in many ways – flat, curved, cylindrical, rigid, flexible etc. They can be large-area or small and pointed – whatever the envisaged application demands. Shown below are some sample SMD sources – the active (plasma producing) electrode is structured (e.g. the 5x5 mm² net-like arrangement) for optimum energy efficiency.

1. Below left - a 10x10 cm² flat Surface Micro Discharge (SMD) cold plasma source.
2. Below middle – a hemispherical SMD molded cold plasma source.
3. Below right – a cylindrical SMD cold plasma source.

The blue light comes from the excitation/de-excitation of atmospheric nitrogen and shows the way in which the discharges follow the structured electrodes, as well as their typical extent of ~ 1 – 2 mm. SMD and DBD plasma sources are usually driven with AC at a few 10s of kHz. The production of micro-discharges can be readily seen in the electrical signature.

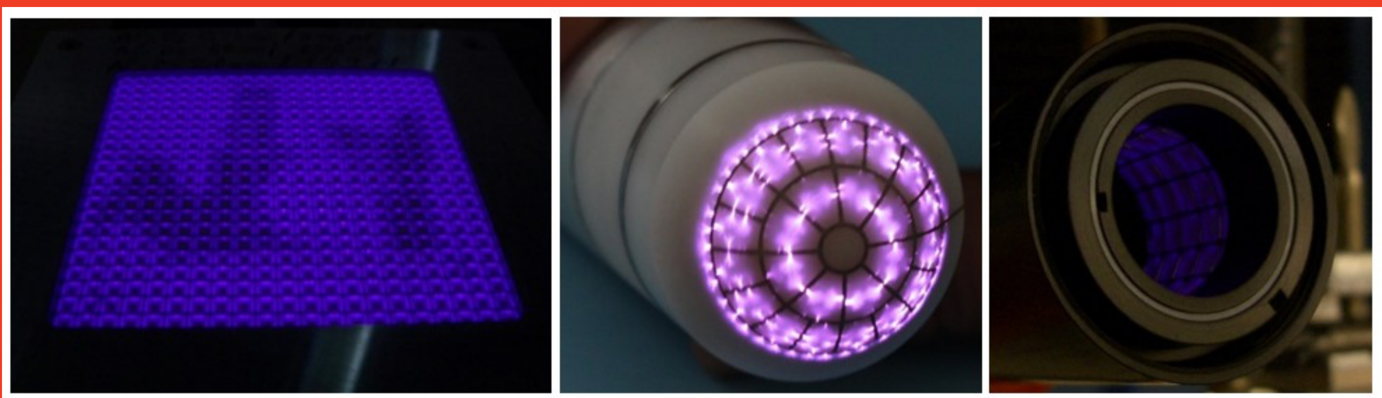


Figure 6: A selection of SMD cold plasma sources developed by terraplasma GmbH.

cold plasma applications

Cold plasma has a range of proven applications in the medical, consumer, water-treatment and agricultural fields, with dozens of devices and applications in the market.
The main effects (or actions) of cold plasma in real-world applications include the following:

Viruses & Bacteria*

Perforation of the outer membrane by thermal, electrostatic and chemical (H-denaturation by e.g. OH, NO_3 radicals) effects.

Viruses*

In addition, damage of the spike protein by electric fields, preventing the virus from docking with cells.

*Build-up of resistance (e.g. AMR) against these processes is very difficult for both viruses and bacteria.

Breaking of molecular chemical bonds

Breaking of molecular chemical bonds by the direct action of energetic (several eV) electrons via the processes of electron impact dissociation and dissociative attachment reactions.

Cancer treatment

Selective action in glioma cells has been observed. These showed a cell cycle arrest (in the G2 phase) when plasma treated, and demonstrate a huge inhibition (factor 5) relative to cells treated with chemotherapy (TMZ) alone.

Cold atmospheric plasma cocktails

Cold atmospheric plasma is unique in that over 600 chemical reactions occur (with the atmospheric 'ingredients' O_2, N_2 and H_2O). By designing the plasma chemistry using appropriate plasma sources and operation, it is possible to optimize the plasma for disinfection, water purification, air purification, wound healing, dermatology, dentistry, plant growth, etc. As an interesting aside – CAP produces the same reactive oxygen and nitrogen species that our human immune system generates to fight infections.

applications - 1

Disinfection & sterilization

One of the earliest identified applications of the use of cold plasma was the ability to disinfect and sterilize. It has been known for a long time that a 'hot plasma' can sterilize efficiently within seconds. Reducing the ion and electron component by over 10 orders of magnitude turned out to also provide very effective disinfection, within few seconds – virtually irrespective of bacteria type!

Cold plasma is highly suitable for disinfection and sterilization due to its ability to inactivate a wide spectrum of pathogens, including bacteria, viruses, fungi, and spores (including AMR) without the need for high temperatures or harmful chemicals.

Its ability to rapidly treat irregular surfaces and penetrate biofilms further enhances its effectiveness, making it adaptable for numerous industries, including healthcare, food safety, water and air purification. With fast action, safety, and sustainability, cold plasma offers a significant technological advantage over many conventional disinfection and sterilization techniques.

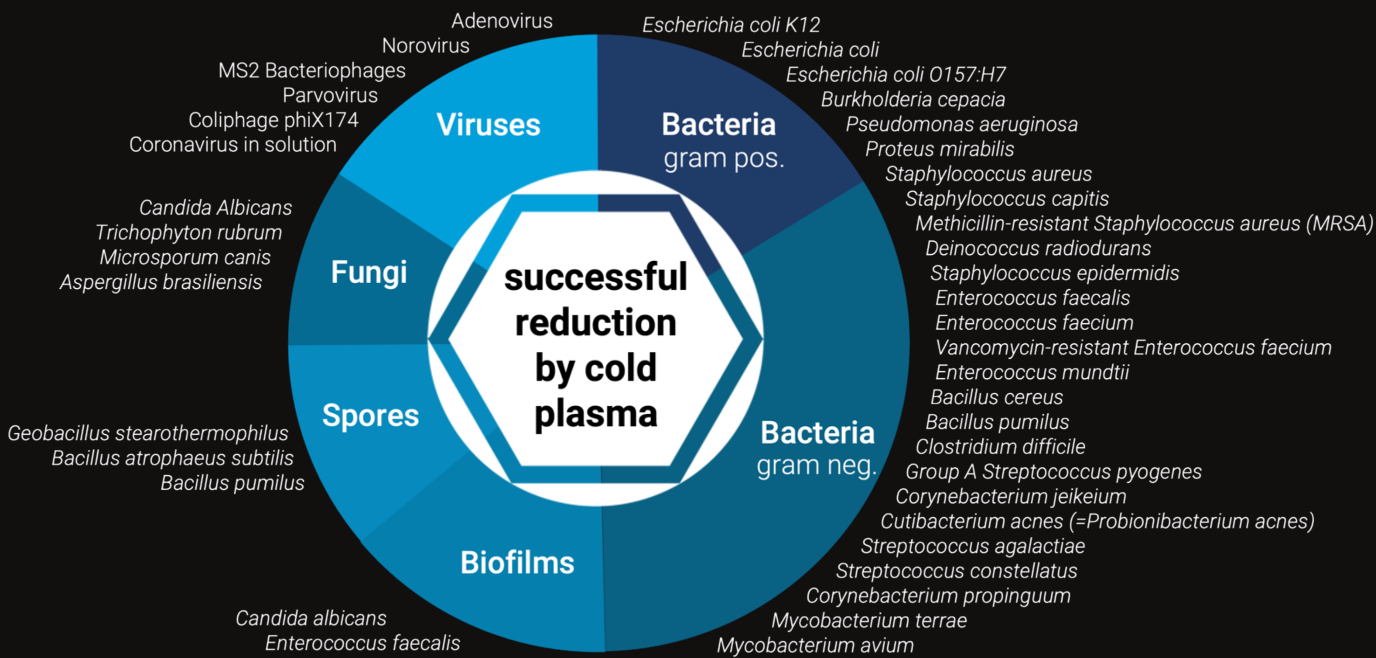


Figure 7: Representative list of microbes treated with cold plasma in standardized lab tests, and some commercial products where the technology has been integrated.

applications - 1

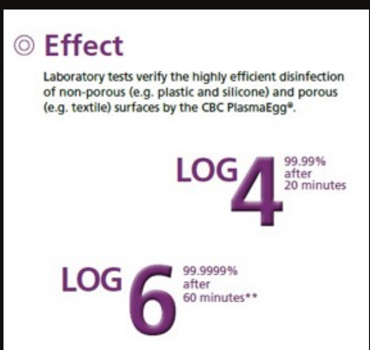
Disinfection & sterilization

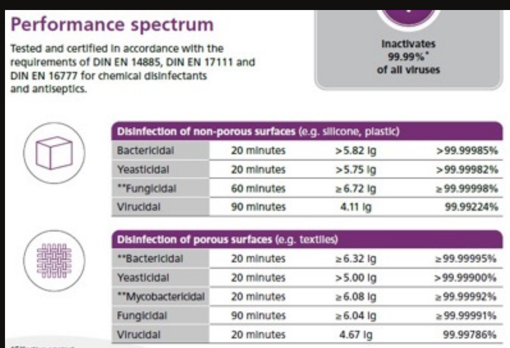
The Kimitec CBC PlasmaEgg® is designed for innovative disinfection of everyday objects, laboratory aparatus, and personal protective equipment. It generates cold atmospheric plasma that targets proteins and the RNA/DNA of bacteria, viruses, and fungi, effectively destroying them. It is also effective against multi-resistant germs.

The innovative, energy-efficient, and resource-saving disinfection technology with cold plasma represents a significant breakthrough and a "market first" in the field of mobile disinfection devices.

CAP disinfection & sterilisation is characterised by good compatibility and fast onset of action. In addition,

- CAP is colourless
- Quick-acting
- Residue-free
- Penetrates narrow areas
- Permeates porous materials
- No shadowing effect
- Unbeatable level of user safety.





Performance spectrum

Tested and certified in accordance with the requirements of DIN EN 14885, DIN EN 17111 and DIN EN 16777 for chemical disinfectants and antiseptics.

Inactivates 99.99%* of all viruses

Disinfection of non-porous surfaces (e.g. silicone, plastic)			
Bactericidal	20 minutes	>5.82 lg	>99.99985%
Yeasticidal	20 minutes	>5.75 lg	>99.99982%
**Fungicidal	60 minutes	≥6.72 lg	≥99.99998%
Virucidal	90 minutes	4.11 lg	99.99224%

Disinfection of porous surfaces (e.g. textiles)			
**Bactericidal	20 minutes	≥6.32 lg	≥99.99995%
Yeasticidal	20 minutes	>5.00 lg	>99.99900%
**Mycobactericidal	20 minutes	≥6.08 lg	≥99.99992%
Fungicidal	90 minutes	≥6.04 lg	≥99.99991%
Virucidal	20 minutes	4.67 lg	99.99786%

applications - 2

Medicine - Chronic and Acute Wounds. Dermatology.

Cold plasma is an established and cutting-edge method for treating (chronic) wounds, with numerous technologies and companies having received medical device approval for their cold plasma treatment systems.

Cold plasma has two primary benefits for the human skin:

1. the effective inactivation of bacteria
2. stimulation of intracellular processes in human (eukaryotic) cells .7-10,

both of which are necessary to heal (infected) wounds.

But cold plasma is also highly effective in dermatology. A large number of medical-scientific cold plasma studies in the dermatological field confirm anti-microbial, anti-itching and anti-inflammatory effects in many skin diseases (e.g. acne, psoriasis, atopic eczema, actinic keratosis, warts, herpes zoster, tinea) with good tolerability. The improved absorption of superficially applied active ingredients in creams, tinctures, etc. are also better absorbed by the skin after a cold plasma application.11-14

Cold plasma has a calming effect on itching and inflammation in diseases such as neurodermatitis or fungal skin infections. A decisive advantage over purely medicinal treatment is that cold plasma is free of allergies and side effects. The treatment is thus rated as painless.

Left: patient being treated with plasma care® by a wound specialist.

plasma care® is an approved Class IIa medical device which uses SMD cold plasma technology for the treatment of chronic and sports wounds and skin issues like acne, rosacea, etc.

plasma care was developed by terraplasma GmbH and is sold by terraplasma medical GmbH.

applications - 2

Medicine - Chronic and Acute Wounds. Dermatology.

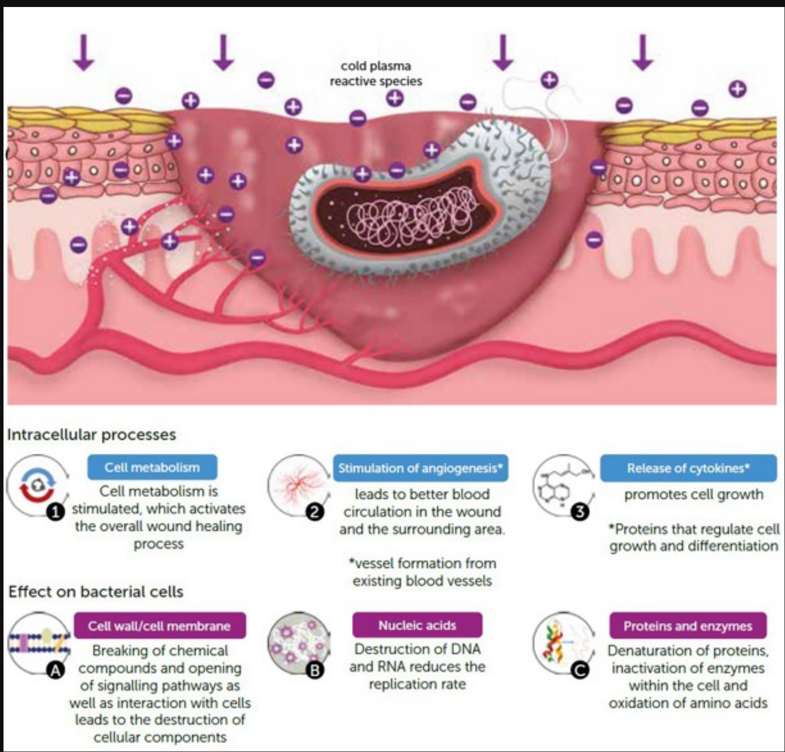


Figure 8: The effects of cold plasma on wounds explained.

Reactive oxygen and nitrogen species (RONS) play a critical role in modulating cellular processes. When applied to wound sites, cold plasma activates signaling pathways that enhance cell proliferation, migration, and angiogenesis—the formation of new blood vessels. These activities collectively boost the supply of nutrients and oxygen to the affected area, accelerating tissue regeneration. the process also optimizes the function of fibroblasts and keratinocytes, cells, essential for collagen synthesis and epidermal repair, leading to faster closure of wounds.

Cold plasma's antimicrobial properties reduce bacterial load in wounds without damaging the surrounding healthy tissue.

Excerpts of published studies with plasma care®

1. Hygcen (2020) skin disinfection test according to VAH Method 13 on natural skin flora and supplemented with E. coli

2. Scheper et al. (2021) Cold plasma therapy with the handheld device plasma care® improves the tendency to heal in problem wounds – 10 case studies from diabetological practice

3. Yuta Terabe et. al. (2021) Using cold plasma to treat chronic foot ulcer infection

4. Yuta Terabe et. al. (2021) Treating hard-to-heal skin and nail onychomycosis of diabetic foot with plasma therapy

5. Brüning et. al. (2021) Using cold atmospheric plasma to treat hard to heal wounds. A case study with 10 Patients (with 19 wounds) treated in a dermatological outpatient clinic

6. Hämmerle et. al. 2021; Positive effects of cold atmospheric plasma on pH in wounds: a pilot study

7. Dejonckheere et. al. 2022. Non-Invasive Physical Plasma for Preventing Radiation Dermatitis in Breast Cancer: A First-In-Human Feasibility Study

8. Deitmerg et. al. 2022; Wundbehandlung mit Kaltplasma

9. Dejonckheere et. al. 2024. Non-invasive physical plasma for preventing radiation dermatitis in breast cancer: Results from an intrapatient-randomised double-blind placebo-controlled trial

10. Ligresti C, et al. Use of Cold Plasma in the Treatment of Infected Wounds. J Surg Res Prac. 2024;5(1):1-10.

inactivation of bacteria

Antimicrobial resistance (AMR) is currently one of the greatest public health threats. Gram-negative bacteria are particularly resistant to many of the antibiotics used to treat severe and hospital-acquired infections.

Fortunately, the build-up of resistance against cold plasma is extremely difficult for both bacteria and viruses. In addition, cold plasma is effective

- Independent of bacteria type.
- Including effective on bacteriacidally resistant bacteria e.g MRSA, Ehec.
- No resistance buildup against cold plasma, as CAP breaches the membrane and attacks the DNA in the cyctoplasma.
- Various physical (e.g. thermal, electro- magnetic) and chemical (e.g. hydrogen denaturation) processes occur simultaneously.
- Gas is able to breach surfaces quickly and penetrates into small cracks (not affected by surface tension, shadowing etc.)

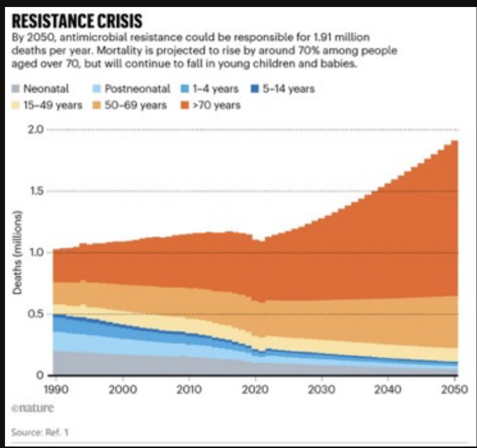
Important examples of antimicrobial resistance strains of bacteria include:

- methicillin-resistant Staphylococcus aureus (MRSA) • vancomycin-resistant Enterococcus (VRE)
- multi-drug-resistant Mycobacterium tuberculosis (MDR-TB)
- carbapenemase-producing Enterobacterales (CPE).

www.betterhealth.vic.gov.au

More than 39 million people will die from antibiotic-resistant infections between now and 2050, according to an in-depth global analysis of antimicrobial resistance.

(Source: www.nature.com)



additional cold plasma applications

In addition to the applications described in the previous pages, there are a number of other applications of cold plasma with well-established market applications, and at varying stages of maturity and market validation.

agriculture	Cold plasma is revolutionizing agriculture by providing sustainable, efficient and chemical-free solutions for pest and pathogen control, precision nutrition, nutrient management, and overall crop health.
water treatment	Cold plasma technology, known as Plasma Activated Water (PAW) is emerging as a solution for water treatment due to its ability to break down contaminants, deactivate pathogens, and remove pollutants effectively, without the need for harsh chemicals or large amounts of energy. Cold plasma has been proven to be highly effective in treating both fresh and grey water, as well as wastewater and industrial effluents which may contain germs, pathogens or complex and persistent pollutants.
reforming of GHGs (greenhouse gases)	The electron impact processes and reactive species production of cold plasma also can be employed in the manufacture and reforming of gases (e.g. CH_4, CO_2, NH_3) – both in their industrial production and for reducing undesired or harmful emissions. A further promising use of cold plasma is “plasma catalysis”, e.g. in dry reforming of methane (CH_4).
odor and allergen control	Cold plasma is highly effective for odor and allergen control due to its ability to break down volatile organic compounds (VOCs) and neutralize airborne particles at a molecular level. The reactive species generated by cold plasma interact with odor-causing molecules and allergens, breaking the chemical chains and degrading them into harmless byproducts like water and carbon dioxide.

cold plasma terminology

Evaluating cold plasma for a specific application? Here are some terms you'll need to know:

cold plasma
partially ionized gas, where the ionization level is sufficiently low, so that the energy required to maintain the low level of plasma does not increase the overall temperature above 40 C.

cold atmospheric plasma
same as cold plasma, except that the 'gas' is air at NTP (Normal Temperature and Pressure).

reactive species
a type of unstable molecule that contains oxygen and that easily reacts with other molecules in a cell. Reactive oxygen species are free radicals. Also called oxygen radical (NCI Definition). In CAP chemistry we differentiate between Reactive Oxygen Species (ROS) that do not contain nitrogen and Reactive Nitrogen Species (RNS) that contain oxygen as well as nitrogen, or both types (RONS).

excited species
atoms or molecules that are temporarily energized to a level above their fundamental state. When these de-excite, the excess energy is emitted in the form of light. An example of this is the blue nitrogen line emission we see when a plasma discharge occurs in air.

plasma characterization
in order to design a plasma for a specified purpose, we need to characterize its properties. The main physical properties are plasma power, ionization level, temperature, and, on the input side - current, voltage and frequency. The chemical properties (in CAP) are generally determined by the relative oxygen- nitrogen preponderance (the usual measurement indicator being ozone).

oxygen mode
usually the low power branch, producing mostly ozone.

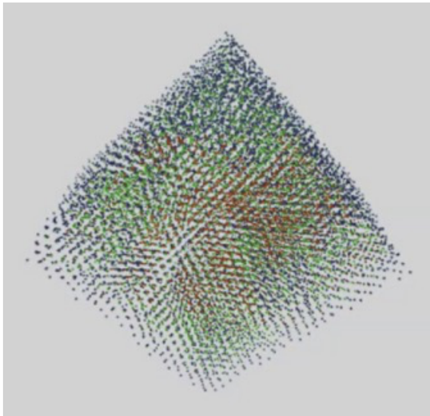
nitrogen oxides mode
usually the high power branch, leading to ozone quenching and enhanced NOx (i.e. NO, NO_2, NO_3, N_2O etc) production.

afterglow
Continued emission of plasma energy after removal from the excitation source. This occurs because of the delayed recombination of excited particles within the substance.

our journey

terraplasma's cold plasma technology has been under development since 1990, initially at Max-Planck and subsequently as a spin-off, beginning in 2014.

Roscosmos cosmonaut Oleg Novitsky working on the Plasma Kristall-4 experiment in Europe's Columbus laboratory on the ISS (June 2021; image credit: ESA/NASA–T. Pesquet)



Three-dimensional plasma crystal: The color coding represents various crystal states, with phase transitions and many other phenomena.

Professional application integrating terraplasma's 5th generation cold plasma module.

terraplasma's cold plasma research aboard the International Space Station (ISS) began in 1999, with the PKE, PK-3plus and PK-4 plasma crystal laboratories spanning over 20 years.
The current laboratory, PK4, is installed in the ESA Columbus Module.

our authors

Prof. Dr. Gregor Morfill
CHIEF SCIENTIST

Prof. Dr. Gregor Morfill is the co-founder of terraplasma GmbH and renowned for his groundbreaking work in astrophysics and plasma physics. After completing his PhD at Imperial College London, Greg held various prestigious positions, including professorships at the Max Planck Institute for Nuclear Physics and Heidelberg University, and served as Director at the Max Planck Institute for Extraterrestrial Physics beginning in 1984. Greg has authored over 500 scientific publications and received numerous awards, including the James Clerk Maxwell Prize for Plasma Physics in 2011.

Dr. Julia Zimmermann
CEO

Dr. Julia Zimmermann is the co-founder and CEO of terraplasma GmbH since 2015, as well as past CEO of terraplasma medical GmbH, with a strategic exit in 2023. Prior to founding terraplasma, she worked at the Max-Planck-Institute for Extraterrestrial Physics and completed her PhD in biophysics at the LMU.

Sylvia Cantzler
HEAD OF GROWTH

Sylvia studied biotechnology and has nearly ten years experience in managing clinical studies as well as developing and maintaining quality management processes (ISO 9001, ISO 13485) for terraplasma's medical and disinfection applications.

Robert Schober
PROJECT MANAGER

Robert studied chemical engineering at TUM and has expertise in developing cold plasma products, including plasma physics and chemistry, electrical engineering, microbiology and product development and management.

Vincent Zenkner
DIRECTOR PRODUCT ENGINEERING

Vincent studied design, majoring in environmental sciences. Prior to joining terraplasma, he worked at UnternehmerTUM helping both start-ups and established companies like BMW and Airbus to develop and implement agile product development processes.

This experienced team combines expertise in technology, marketing, operations, and finance to drive terraplasma's success and growth.

our partners

stay tuned for...

hyped about science

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